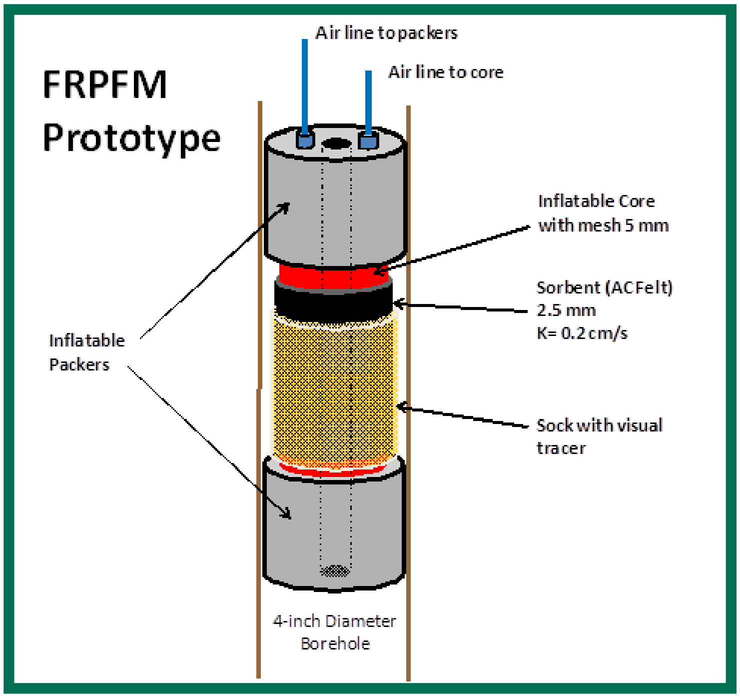
ESTCP
Cost and Performance Report

(ER-200831)



Demonstration and Validation of a Fractured Rock Passive Flux Meter

April 2015

ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
30-03-2015	Cost & Performance Report	04/2008-03/2015

4. TITLE AND SUBTITLE Demonstration and Validation of a Fractured Rock Passive Flux Meter (FRPFM)	**5a. CONTRACT NUMBER** W912HQ-08-C-0012
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Kirk Hatfield	**5d. PROJECT NUMBER** ER-200831
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Florida PO Box 116580 365 Weil Hall Gainesville, FL 32611	**8. PERFORMING ORGANIZATION REPORT NUMBER** C&P-ER-200831
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Andrea Leeson 4800 Mark Center Drive, Suite 17D08 Alexandria, VA 22350-3605	**10. SPONSOR/MONITOR'S ACRONYM(S)** ESTCP
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The overall objective of this project was to demonstrate and validate a new closed-hole passive sensing technology for fractured media: the Fractured Rock Passive Fluxmeter (FRPFM). The FRPFM provides simultaneous measurement of (1) the presence of flowing fractures, (2) the location of active or flowing fractures; (3) active fracture orientation i.e., dip and azimuth; (4) direction of groundwater flow in each fracture; (5) cumulative magnitude of groundwater flux in each fracture; and (6) cumulative magnitude of contaminant flux in each fracture. Various technologies exist to measure (1), (2) and (3) above; however, the FRPFM is the only technology that also measures (4), (5) and (6).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
U	U	U	None	66	Kirk Hatfield
					19b. TELEPHONE NUMBER *(Include area code)* 352-392-9537

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

COST & PERFORMANCE REPORT
Project: WP-200831

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ACRONYMS AND ABBREVIATIONS

ATV	acoustic televiewer
bgs	below ground surface
BHD	borehole dilution
cm^2/day	square centimeters per day
DCE	cis-1,2-dichloroethene
DNAPL	dense nonaqueous phase liquid
DoD	Department of Defense
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FRPFM	Fractured Rock Passive Fluxmeter
GTS	Guelph Tool Site
HRTP	high resolution temperature profile
IFL	impermeable flexible liner
µg/L	microgram per liter
MNA	monitored natural attenuation
NAWC	Naval Air Warfare Center
OTV	optical televiewer
PFM	passive fluxmeter
PI	Principal Investigator
PVC	polyvinyl chloride
SERDP	Strategic Environmental Research and Development Program
TCE	trichloroethylene
TVP	temperature vector probe
USGS	U.S. Geological Survey
VC	vinyl chloride

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ACKNOWLEDGEMENTS

We gratefully acknowledge the financial and technical support provided by the Environmental Security Technology Certification Program (ESTCP) including the guidance provided by Dr. Andrea Leeson (Environmental Restoration Program Manager). We would also like to thank all individuals and organizations that provided extensive guidance and support for this project.

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EXECUTIVE SUMMARY

Complex hydrogeologic conditions such as fractured and karst bedrock settings pose substantial economic and technical challenges both to the characterization and remediation of dense nonaqueous phase liquid (DNAPL) source zones. The Army Environmental Center lists 34 installations where restoration may be technically impractical, even with a budget of $3 billion (approximately 50% of the Army's total projected environmental restoration budget). Of the 34 installations, 26 are underlain by complex fractured rock or karst aquifers.

To reduce the cost of characterization and remediation of fractured rock sites, it is critical to identify candidate sites for Monitored Natural Attenuation (MNA) and prioritize the remaining sites for remediation. To assist in this endeavor, cost-effective monitoring tools are needed that can be used in concert with existing borehole technologies to directly measure groundwater and contaminant flux in fractured rock. These flux measurements combined with data gathered from other available borehole technologies will bring the Department of Defense (DoD) much closer to estimating contaminant mass discharge from source zones and in turn expedite assessments of environmental risks and benefits associated with natural attenuation, source removal, or remediation at complex sites.

OBJECTIVE OF THE DEMONSTRATION

The overall objective of this project was to demonstrate and validate a new closed-hole passive sensing technology for fractured media: the Fractured Rock Passive Fluxmeter (FRPFM). The FRPFM provides simultaneous measurement of: (1) the presence of flowing fractures; (2) the location of active or flowing fractures; (3) active fracture orientation, i.e., dip and azimuth; (4) direction of groundwater flow in each fracture; (5) cumulative magnitude of groundwater flux in each fracture; and (6) cumulative magnitude of contaminant flux in each fracture. Various technologies exist to measure (1), (2), and (3) above; however, the FRPFM is the only technology that also measures (4), (5), and (6).

The specific objectives of this demonstration were:

1. Demonstrate and validate an innovative technology for the direct in situ measurement of cumulative water and contaminant fluxes in fractured media;
2. Formulate and demonstrate methodologies for interpreting contaminant discharge from point-wise measurements of cumulative contaminant flux in fractured rock; and
3. Enable the technology to receive regulatory and end user acceptance.

TECHNOLOGY DESCRIPTION

The FRPFM is designed with an inflatable core and separate upper and lower end packers. The core is simply a packer (or flexible inflatable liner) covered with an internal nonreactive layer of permeable mesh that is wrapped in a permeable layer of material derived from activated carbon, ion exchange resin, or similar sorbent material impregnated with tracers. Then, all of this is encased in a thin external permeable layer of cloth material impregnated with a visible dye. The core inflates separately from the two end packers to provide a mechanism for holding the one or

more reactive fabrics against the face of the borehole and any fracture intersecting that borehole, while the end packers isolate the zone of interest from vertical hydraulic gradients within the borehole. As currently designed, the FRPFM provides high resolution measurements over a specified interrogation zone (typically 1 meter).

Deploying the FRPFM in a borehole and exposing it to flowing groundwater for duration *t* [T] gradually leaches visible dyes and tracers from the internal and external sorbent layers and produces residual dye and tracer distributions. Visual inspection of the external layer impregnated with a visible dye leads to estimates of the following for active or flowing fractures alone: (1) locations along the borehole; (2) number; (3) individual fracture orientations in terms of strike, dip, and orientation of dip (direction of falling dip, e.g., southwest); (4) cumulative groundwater flux; and (5) groundwater flow direction. Fracture characteristics (1) through (3) can be obtained through existing borehole imaging technologies as long as those fractures possess apertures $\geq$1mm; however, these commercially available technologies cannot distinguish active from inactive fractures or measure the magnitude or direction of fracture flow. Further analytical analysis of the FRPFM internal sorbent layer at indicated locations of active fractures yields: (1) additional estimates of cumulative groundwater flux in fractures; and (2) cumulative contaminant flux in those fractures. Thus, the in situ measurements of direction and magnitude of water and contaminant fluxes in active fractures are innovations given by the FRPFM alone.

DEMONSTRATION RESULTS

In support of the first demonstration objective listed above, this report defines six specific technology performance objectives and establishes metrics to compare FRPFM measures (contaminant and groundwater fluxes, flow direction, detection of active flowing fractures, fracture location and orientation) to those obtained from five different competing/comparative technologies: high resolution temperature profiling (HRTP), acoustic televiewer (ATV), optical televiewer (OTV), temperature vector probe (TVP), and borehole dilution (BHD). Field tests were conducted at two chlorinated solvent contaminated fractured rock sites. This report presents 16 separate field tests and their results. A total of nine down-hole tests were executed in 4- and 6-inch rock wells at the Guelph Tool Site in Ontario Canada and another seven tests were conducted in one 6-inch rock well located on the premises of the former Naval Air Warfare Center in West Trenton, New Jersey. Based upon the results of the 16 field tests, the FRPFM achieved the standard in each of the six quantitative performance objectives.

In support of the second demonstration objective, methodologies were formulated and demonstrated for interpreting contaminant discharge from point-wise measurements of cumulative contaminant flux in fractured rock. Those methods were published in a highly ranked peer-reviewed journal *Water Resources Research* (Acar et al., 2013).

In support of the third project objective, Enviroflux Inc. assumed exclusive rights to commercialize the FRPFM technology (patented in 2008). At this time, Enviroflux Inc. is engaged in discussions to deploy FRPFMs for a major client of a large environmental firm. The Environmental Protection Agency (EPA) has also shown interest in continued field testing and site selection is under way.

IMPLEMENTATION ISSUES

The FRPFM technology currently functions through deployment of custom-built prototypes designed with a specified interrogation zone (typically 1 meter). Currently, prototypes exist for application in 4-inch and 6-inch fractured rock wells. Deployment, retrieval, and sampling is straightforward and has been demonstrated to field technicians from the University of Guelph and U.S. Geological Survey (USGS) who experienced minimal issues with methodology transfer.

Depending on site conditions, permits may be required for permission to release small quantities of food-grade tracers into the aquifer. A standard list of tracers is available, and no issues have been experienced with previous permit requests.

As technology development continues, refinements will be made and applied to future prototypes (such as expanded interrogation zone). Site specific refinements can be made as needed.

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1.0 INTRODUCTION

1.1 BACKGROUND

Complex hydrogeologic conditions such as fractured and karst bedrock settings pose substantial economic and technical challenges both to the characterization and remediation of dense nonaqueous phase liquid (DNAPL) source zones. The Army Environmental Center lists 34 installations where restoration may be technically impractical, even with a budget of $3 billion (approximately 50% of the Army's total projected environmental restoration budget). Of the 34 installations, 26 are underlain by complex fractured rock or karst aquifers.

The challenge of estimating cross-sectional discharge (integrated flux) in fractured media is quite different and perhaps much more difficult than granular media for various reasons. One of which is variations in fracture aperture between borehole (Novakowski et al., 2006), and another being some fractures are large and perhaps important hydraulically, while others are small and significant in the context of controlling plume structure. It is also important to keep in mind that contaminant flux in fractures can be approximated as the product of fracture flow and contaminant concentration. Some fractures can possess high contaminant concentrations but produce low fluxes because flow is negligible; whereas, in others concentrations can be low, but the fluxes high because flow is significant. Thus, it is not possible to identify fractures producing significant contaminant fluxes viewing concentration without flow and vice-versa. Finally, with respect to estimating contaminant discharge, it is pertinent to recognize the importance of fracture density. Small fractures, that individually produce low contaminant fluxes, can generate large contaminant discharges at the transect scale if fracture density is significant.

This report presents results of a technology demonstration/validation study where cumulative or time-averaged water and contaminant fluxes were measured in fractured rock aquifers under ambient closed-hole conditions. Usually water and contaminant fluxes are estimated from observed contaminant concentrations in fractured rock boreholes and depth-average groundwater flows calculated or measured under open-hole conditions. This approach typically requires extensive aquifer characterization and costly flow and water quality monitoring in open boreholes. Hydrophysical logging, pulse flow meters (Model 40 GEOFLO), acoustic Doppler velocimeters, and colloidal borescopes are tools typically used that reveal much about fractured flows towards an open borehole (Wilson et al., 2001). Unfortunately, open borehole techniques are not likely to produce accurate estimates of ambient contaminant discharge for at least two reasons. First, open boreholes induce magnitude and directional changes in water and contaminant fluxes in fractures and between fractures that do not exist naturally as in the absence of a borehole. Hence, flows that do not occur under natural aquifer conditions are not likely to produce concentrations and depth-average discharges that represent ambient conditions. Second, water and contaminant fluxes vary significantly between fractures and over time; therefore, typical short-term or instantaneous measurements of flow and concentration do not generate representative long-term projections of flow, concentration, and contaminant discharge.

Closed-hole conditions are preferred for making ambient water and contaminant flux measurements. These conditions are closely approximated using FLUTe™ and packers to isolate borehole sections (Cherry et al., 2007). These devices eliminate the exchange of water and contaminant between fractures that occurs in open boreholes and in turn restore nature flows in

fractures. FLUTe™ has been used with high resolution temperature logging techniques to locate and rank active (flowing) fractures under closed-hole conditions. Beyond this study and to the best of our knowledge, individual fractured flows have not been measured under closed-hole conditions; however, isolated and depth-integrated fracture flows have been measured over isolated sections of a borehole using the point or borehole dilution method (Guitierrez et al., 1977; Xu et al., 1997; and Novakowski et al., 2006). Furthermore, direct measures of contaminant fluxes in fractures have not been reported. As a result, measurement and/or calculation of flux at the fracture scale are somewhat novel. Hence, published accounts of water or contaminant discharge estimated over fractured transects are almost non-existent (Acar et al., 2013; Plett, 2006; and Novakowski et al., 2006).

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this project was to demonstrate and validate the fractured rock passive flux meter (FRPFM) as new technology that measures the magnitudes and directions of cumulative water and contaminant fluxes in fractured rock aquifers. The specific project objectives were:

1. Demonstrate and validate an innovative technology for the direct in situ measurement of cumulative water and contaminant fluxes in fractured media;
2. Formulate and demonstrate methodologies for interpreting contaminant discharge from point-wise measurements of cumulative contaminant flux in fractured rock; and
3. Enable the technology to receive regulatory and end user acceptance.

1.3 REGULATORY DRIVERS

To reduce the cost of characterization and remediation of fractured rock sites, it is critical to identify candidate sites for Monitored Natural Attenuation (MNA) and prioritize the remaining sites for remediation. To assist in this endeavor, cost-effective monitoring tools are needed that can be used in concert with existing borehole technologies to directly measure groundwater and contaminant flux in fractured rock. These flux measurements combined with data gathered from other available borehole technologies will bring the Department of Defense (DoD) much closer to estimating contaminant mass discharge from source zones and in turn expedite assessments of environmental risks and benefits associated with natural attenuation, source removal, or remediation at complex sites.

For fracture bedrock sites, a significant cost savings to DoD could be realized if certain sites were quantitatively found to pose little off-site risk due to natural attenuation. Based upon projected remediation costs of approximately $3 billion per 34 difficult installations, it was estimated that approximately $2.3 billion could be spent on 26 sites underlain by fractured rock and karst aquifers (SERDP and ESTCP Workshop, 2006). The greatest cost savings could be realized in less than 5 years, if FRPFM monitoring determined at any one site, natural attenuation was sufficient and active remediation could be avoided.

2.0 TECHNOLOGY

The technology demonstrated and validated in this project is a new closed-hole passive sensing technology for fractured media: the FRPFM. The FRPFM provides simultaneous measurement of: (1) the presence of flowing fractures; (2) the location of active or flowing fractures; (3) active fracture orientation, i.e., dip and azimuth; (4) direction of groundwater flow in each fracture; (5) cumulative magnitude of groundwater flux in each fracture; and (6) cumulative magnitude of contaminant flux in each fracture. Various technologies exist to measure (1), (2), and (3) above; however, the FRPFM is the only technology that also measures (4), (5), and (6).

The FRPFM is essentially an inflatable packer or flute that holds one or more reactive fabrics against the wall of a borehole and to any water-filled fractures intersected by a borehole. These reactive fabrics are designed to intercept and retain target groundwater contaminants (i.e., trichloroethylene [TCE], cis-1,2-dichloroethene [DCE], vinyl chloride [VC]); in addition, these fabric release non-toxic tracers, some of which visibly indicate active fracture location, orientation, and direction of fracture flow along a borehole, while others quantify cumulative groundwater discharge in these fractures.

Demonstration and validation studies were conducted at two sites where available field facilities permitted FRPFM testing in well-characterized rock wells and underlying fractured rock aquifers were contaminated with chlorinated solvents. Direct FRPFM measures of active fracture location, orientation, direction and magnitude of water and contaminant fluxes were compared to results generated using competing technologies (e.g., borehole imaging tools, high resolution temperature logging, and borehole dilution). The project demonstrated that the FRPFM was particularly cost-effective for fractured rock characterization and monitoring when used in concert with other borehole technologies (e.g., high resolution temperature logging). The project also demonstrated methods for interpreting water and contaminant discharge from a single well or transect of multiple boreholes (Acar et al., 2013).

2.1 TECHNOLOGY DESCRIPTION

Complex hydrogeologic conditions such as fractured bedrock and karst settings pose substantial challenges both to the characterization and remediation of DNAPL source zones. Cost-effective quantification of contaminant discharge is critical at complex sites in order to assess long term risk, evaluating remedial performance, and achieving regulatory compliance. For fracture bedrock sites, a significant cost savings to DoD can be realized if certain sites are quantitatively found to pose little off-site risk, or they do not require active remediation because contaminant mass discharge is low and can be attenuated by natural processes. Various open-hole technologies exist to locate fractures, measure fracture apertures, and determine fracture orientations in terms of strike, dip, and dip orientation (direction of falling dip, e.g., southwest), and other technologies exist that measure fracture flows under open-hole conditions. Unfortunately, as stated above, open boreholes induce fracture flows that are not natural or ambient; consequently, open-borehole techniques are not likely to produce accurate estimates of ambient contaminant discharge. Monitoring tools that function in closed boreholes are needed to measure ambient water and contaminant flux in fractured rock. To be cost-effective in the field, these novel tools must generate complementary data to existing borehole technologies.

2.1.1 Technology Overview

The FRPFM constitutes a new closed-hole passive sensing technology for fractured media. The sensor can be deployed at any depth provided that the unit is placed in a saturated flow system. The FRPFM functions like an inflatable (or mechanically expandable) packer or an impermeable flexible liner that holds one or more reactive permeable fabrics against the wall of the borehole and to any water-filled fractures intersected by the borehole.

The FRPFM incorporates novel methods for measuring DNAPL and water fluxes in fractures, but also retains many of the field-tested concepts of the passive fluxmeter (PFM) developed under Environmental Security Technology Certification Program (ESTCP) project ER-0114 (Hatfield et al., 2004; Annable et al., 2005; and Klammler et al., 2007). For example, reactive fabrics function to intercept and retain target groundwater contaminants (i.e., TCE, DCE, VC) and release non-toxic resident tracers (e.g., visible dyes and branch alcohols). The original PFM was design for use in screened wells; however, installations in deep screened wells can be difficult. In addition, this original system was not designed to preclude the unwanted vertical exchange of flow between fractures in rock wells. Thus, a new PFM design was needed that functions under closed-hole conditions in fractured rock wells and is easily installed in deep wells.

Figure 1 illustrates an idealized profile view of a FRPFM intercepting fractures and matrix fluid flow over a given borehole depth. Figure 2 represents a plan view or horizontal cross-sectional view of the same FRPFM in a borehole. Both figures clearly show the device composed of an impermeable flexible liner (IFL), such as the commercially available technology sold under the brand name FLUTe™ (Keller et al., 2007), and permeable reactive sorbent layers (or fabric) sandwiched between the IFL and the borehole circumference. The sorbent is a permeable fabric derived from activated carbon, ion exchange resin, etc. The IFL is made of a fluid impermeable flexible material typically available in a tube or sock design that is easily fitted into a borehole or equivalent aperture in a formation. Once inserted, it is inflated with a fluid to cause it to conform to the shape of the borehole. Hence, the FRPFM is essentially a sampling device with thin permeable layers of one or more removable sorbents attached to the outside surface of an IFL. Such a configuration allows the permeable sorbent layers to be pressed against the well screen or borehole wall when the fluxmeter is inserted and inflated. The sorptive layers passively intercept portions of both fracture and matrix flows in order to simultaneously measure local cumulative solute fluxes and groundwater fluxes. Because the IFL itself is impermeable, fracture flow does not enter the borehole, but is instead diverted around the IFL.

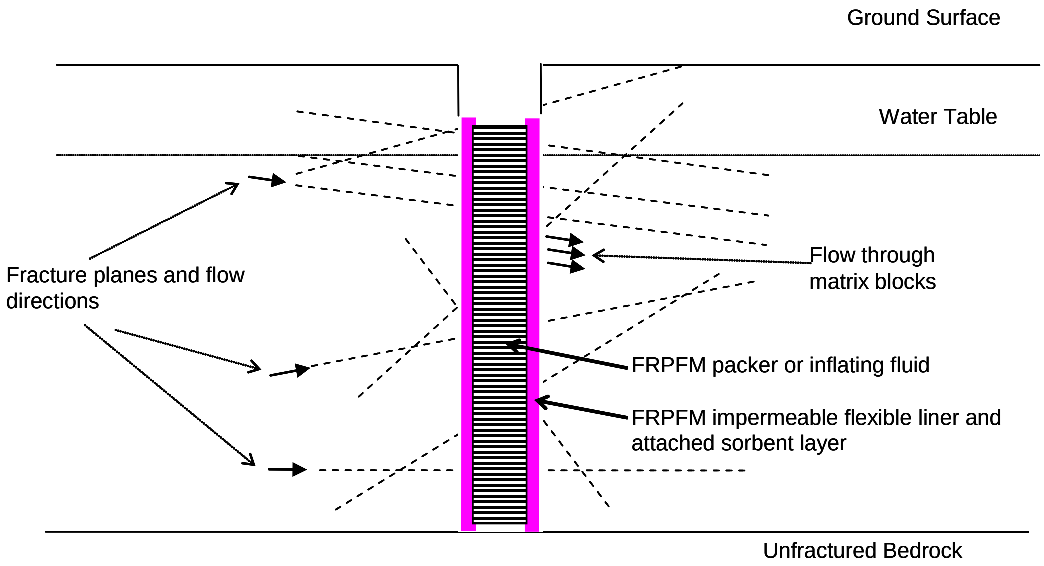

Figure 1. A profile view of an unscreened borehole containing a FRPFM.

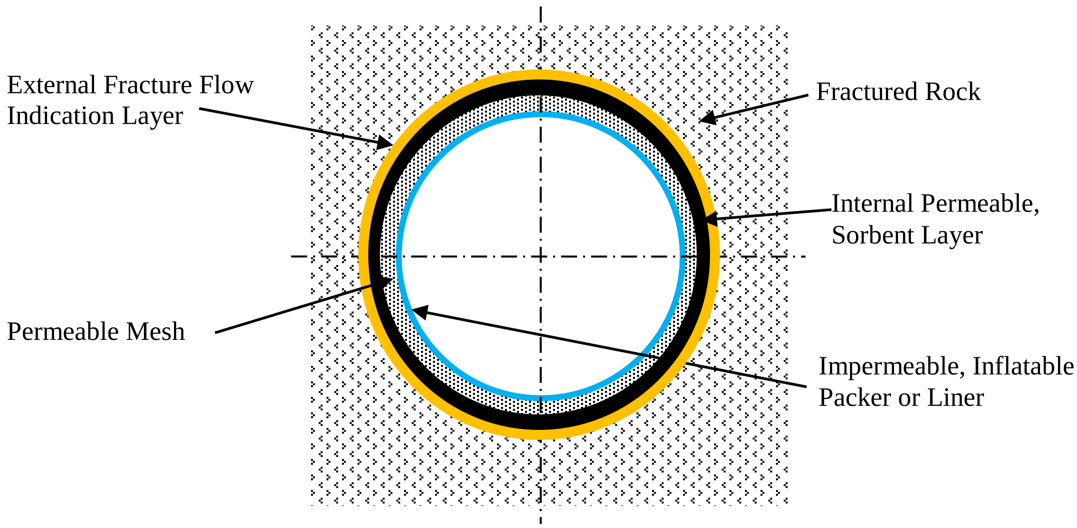

Figure 2. Horizontal cross-section of an FRPFM in an unscreened borehole.
The FRPFM core is composed of an inner impermeable inflatable packer or flexible liner, surrounded by a permeable layer of nonreactive mesh layer, surrounded by an internal permeable reactive sorbent layer (or fabric), and an external fracture flow visual indication layer.

Figure 3 illustrates a second FRPFM system design, which is much shorter in length (~1-2 m) and easier to deploy over target depths. This system is designed with an inflatable core and separate upper and lower end packers. The core is simply a packer (or flexible inflatable liner) covered with an internal nonreactive layer of permeable mesh that is then wrapped in a permeable layer of material derived from activated carbon, ion exchange resin, or similar sorbent material. Then, all of this is encased in a thin external permeable layer of cloth material impregnated with a visible dye. The core inflates separately from the two end packers to provide a mechanism for sealing the core against the face of the borehole, while the end packers isolate the zone of interest from vertical gradients within the borehole. For this project, FRPFM testing was limited to system design illustrated in Figure 3.

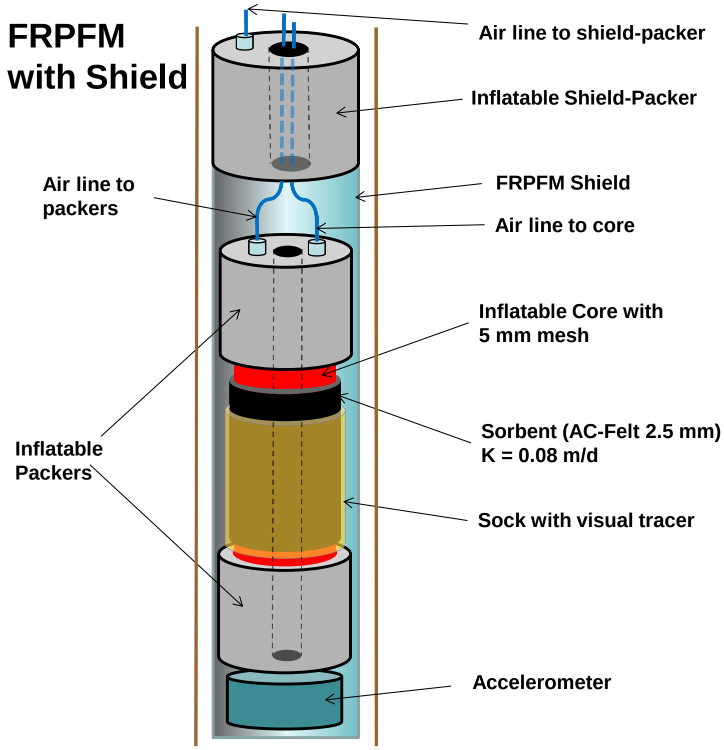

Figure 3. FRPFM designed with an inflatable core and separate upper and lower end packers.

The core is composed of an inner impermeable inflatable packer or flexible liner, surrounded by a permeable layer of nonreactive mesh layer, surrounded by an internal permeable reactive sorbent layer (or fabric), and an external fracture flow visual indication layer.

Exposing the FRPFM to flowing groundwater for duration t [T] gradually leaches the tracer from sorbent layers and produces residual tracer distributions. Visual inspection of the external fracture flow indication layer leads to estimates of the following for active or flowing fractures: (1) locations along the borehole; (2) number; (3) individual fracture orientations in terms of strike, dip, and orientation of dip (direction of falling dip, e.g., SW); (4) cumulative groundwater flux; and (5) groundwater flow direction. Fracture characteristics (1) through (3) can be obtained through existing borehole imaging technologies as long as those fractures possess apertures ≥1mm; however, these commercially available technologies cannot distinguish active from inactive fractures or measure the magnitude of fracture flow or flow direction. Further analytical analysis of the internal sorbent layer at indicated locations of active fractures yields: (1) additional estimates of cumulative groundwater flux in fractures; and (2) cumulative contaminant flux in fractures. Thus, the in situ measurements of direction and magnitude of water and contaminant fluxes in active fractures are **innovations** given by the FRPFM alone.

2.1.2 Field Implementation and Groundwater and Contaminant Flux Interpretation

The FRPFM will typically be deployed in deep fractured rock wells or in deep wells screened in fractured rock or unconsolidated materials. To achieve cost-efficiencies in characterizing rock wells, FRPFM deployments will likely follow after other characterization tools (e.g., high resolution temperature logging [Pehme et al., 2010 and 2014], contaminant profiling [Sterling et

al., 2005], K-profiling or hydraulic conductivity profiling using a FLUTe™ [Keller et al., 2007], etc.) have been used to locate contaminated active fractures and/or fractures believed to conduct the flows under closed-hole conditions. Following a specific deployment period in the rock well, the FRPFM is retrieved and the reactive fabrics removed from the unit for multiple analyses. First the external fracture flow indication fabric is inspected for evidence of visible tracer loss (indicating the location, orientation, and cumulative water flux of flowing fractures). The location of active fractures should compare well fracture locations predicted by high resolution temperature profiling in a FLUTe™ (Pehme, 2013). Next the internal FRPFM sorbent fabric is extracted for retained contaminants and residual resident tracer(s) to generate estimates of cumulative contaminant fluxes and additional estimates of cumulative water fluxes.

Because the FRPFM provides data on descriptive fracture parameters including locations, strike, dip, and dip orientation. This information can be represented using classical hemispherical projections (e.g., Priest, 1985; Lisle and Leyshon, 2004), which is a standard tool for geologists and engineers. Fracture planes may be represented as great circles or poles of the normals to fracture planes and sets of similar fracture plane orientations may be defined. Furthermore, because FRPFMs generate measures of flux in fractures plane, hemispherical projections offer the possibility of simultaneously representing the directions of the groundwater (and contaminant) fluxes in each plane.

The visible tracers used on the FRPFM indicate the magnitude and the direction of groundwater flux in a fracture plane. However, a preferential orientation of fracture planes can introduce an apparent anisotropy in the flow domain, i.e., the directions of the hydraulic gradient and groundwater flow may differ. For this case standard vector algebra or hemispherical plots can be used to obtain the direction of the ambient hydraulic gradient from the local flow directions in two non-parallel fracture planes. Thus, a FRPFM transect of several boreholes will yield a matrix of local flux measurements, where hemispherical plots for each borehole location can be compared to assess geological continuity over the sampled transect and to identify fracture sets of similar orientation. After determining the direction of the hydraulic gradient and individual fracture orientations, measured local groundwater fluxes can be used to identify fractures of higher and lower conductivity. This conductivity information can be compared to data gathered by K-profiling (Keller et al., 2007). Assuming planar fractures and knowing both the locations of intersections within boreholes and fracture orientations, it may be possible to map intersections of factures common between boreholes.

2.1.3 Groundwater and Contaminant Discharges Interpretations

Quantifying water and contaminant mass discharges from a source area or at compliance boundaries in fracture rock is extremely complicated (Acar et al., 2013). However, discharge estimates and their associated estimation errors are critical to characterizing off-site risks and quantifying the effectiveness of active remediation and/or natural attenuation. Multiple complications evolve from spatial variations in fracture characteristics and discontinuities in contaminant distribution (i.e., some fractures are contaminated and others not). To initiate a first-order interpretations of groundwater and contaminant discharges, local measurements of groundwater and contaminant fluxes from a borehole transect can be decomposed into their three spatial components and represented separately in transect contour plots. This representation contains information on location and magnitude ignored by hemispherical plots (described

above) and allows for an investigation of local trends in the measurements (e.g., contaminant plume extension). For example, local groundwater and contaminant flux variability can be analyzed using standard geostatistical techniques (e.g., histogram). Spatial integration of each of flux components, appropriately weighted by facture densities, leads to respective spatial components of groundwater and contaminant discharges. If however, the monitoring network is regular (no preferential sampling pattern) local fluxes can be geometrically added, averaged (using local fracture densities as weights), and multiplied by the transect area to estimate transect discharge and indicate the magnitude and principal (effective) direction of groundwater flow and transport. Again, these discharge estimates are at best first-order approximations; but, they can prove useful in evaluating remediation performance, natural attenuation, and off-site risk. Furthermore, an analysis of errors can follow to examine estimation uncertainties. For example, one may consider uncertainties in the orientation of FRPFMs in the borehole, and to facilitate this analysis hemispherical projection methods exist.

Under the second project objective, multiple methods were published for estimating groundwater contaminant mass discharges and estimation uncertainties from point measures of FRPFM data gathered from one or more boreholes (Acar et al., 2013). These method use data on fracture orientations, fracture frequencies, groundwater flow directions, and water and contaminant fluxes were included in a generalized probabilistic framework. The utility and value of these methods and their water and contaminant mass discharge estimates are enhanced when used in concert with other borehole technologies. For example other logging methods used to target FRPFM deployments to limited sections of a borehole will reduce monitoring and characterization costs.

2.2 TECHNOLOGY DEVELOPMENT

The FRPFM is patented (Klammler et al., 2008) closed-hole passive sensor technology for characterizing water and contaminant mass fluxes in fractured media. This technology uses many of the field-tested concepts of the original PFM system developed under a previous ESTCP funding (ER-0114). Each and every FRPFM component is available from commercial vendors. Packers can be constructed in-house or acquired from multiple manufactures (e.g., FLUTe™ and Solinst LTD). Reactive fabrics such as polyacrylonitrile tissues, activated carbon cloth, etc., can be ordered from various suppliers (e.g., Army-Technology, and Eco-tec-Inc.). Developed in the section that follows is flow and transport theory pertinent to understanding how the FRPFM functions in a fracture rock borehole. Presented are the derivations for the fundamental equations for estimating ambient cumulative water flux in fractured media using visible tracers and residual tracer masses. Also developed are equations for quantifying cumulative contaminant mass fluxes in fracture rock from contaminant mass intercepted and retained on the internal FRPFM sorbent. Appearing in Section 5.3 are results from FRPFM tests conducted in the laboratory and in Section 5.5 results from demonstration/validation tests conducted in the field.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The FRPFM provides simultaneous measurement of six data types with regard to actively flowing fractures: (1) the presence of flowing fractures; (2) the location of active or flowing fractures; (3) active fracture orientation, i.e., dip and azimuth; (4) direction of groundwater flow in each fracture; (5) cumulative magnitude of groundwater flux in each fracture; and (6)

cumulative magnitude of contaminant flux in each fracture. Various technologies exist to measure (1), (2), and (3) above; however, the FRPFM is the only technology that also measures (4), (5), and (6).

Deploying the FRPFM in a borehole and exposing it to flowing groundwater for duration t [T] gradually leaches visible dyes and tracers from the internal and external sorbent layers and produces residual dye and tracer distributions. Visual inspection of the external layer impregnated with a visible dye leads to estimates of five types of information for actively flowing fractures: (1) locations along the borehole; (2) number; (3) individual fracture orientations in terms of strike, dip, and orientation of dip (direction of falling dip, e.g., southwest); (4) cumulative groundwater flux; and (5) groundwater flow direction. Fracture characteristics (1) through (3) can be obtained through existing borehole imaging technologies as long as those fractures possess apertures ≥1mm; however, these commercially available technologies cannot distinguish active from inactive fractures or measure the magnitude or direction of fracture flow. Further analytical analysis of the FRPFM internal sorbent layer at indicated locations of active fractures yields: (1) additional estimates of cumulative groundwater flux in fractures; and (2) cumulative contaminant flux in those fractures. Thus, the in situ measurements of direction and magnitude of water and contaminant fluxes in active fractures are innovations given by the FRPFM alone.

As currently designed, the FRPFM provides high resolution measurements over a specified interrogation zone (typically 1 meter). Due to the high resolution nature of the FRPFM technology, its optimum application would be for characterizing targeted borehole depth intervals and not for screening conditions over an entire borehole. FRPFM prototypes tested in this project were used to interrogate 1 meter depth intervals in 4-inch and 6-inch fractured rock wells.

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3.0 PERFORMANCE OBJECTIVES

The FRPFM provides simultaneous measurement of six independent quantities: (1) the presence of flowing fractures, (2) the location of active or flowing fractures; (3) active fracture orientation i.e., dip and azimuth; (4) direction of groundwater flow in each fracture; (5) cumulative magnitude of groundwater flux in each fracture; and (6) cumulative magnitude of contaminant flux in each fracture. These measures are the basis of the six quantitative performance objectives summarized in Table 1, which lists all quantitative and qualitative performance objectives evaluated during field demonstration of the FRPFM. With regards to the quantitative performance objectives, it is understood that future field application of the technology is contingent upon rigorous statistical comparison of FRPFM measures (e.g., solute and groundwater fluxes, flow direction, active fracture location and orientation) to those obtained using conventional/comparative technologies. Thus, as part of this demonstration, statistics are presented and comparisons made between FRPFM measures for each qualitative performance objective and those obtained by alternative fracture rock technologies in section 6 of this report.

Table 1. Performance objectives.

Performance Objective		Data Requirements	Success Criteria
Quantitative Performance Objectives			
1	Detection of flowing fractures	Measures from visible and non-visible FRPFM tracers and comparative technologies	Detect presence of flowing fractures within +/- 10%
2	Fracture location (depth)	Measures from visible and non-visible FRPFM tracers and comparative technologies	Detect fracture location (depth) within +/- 10%
3	Fracture orientation	Visible dye measures and measures from comparative technology	Measurement validation to within *+/- 15%*
4	Fracture flow direction	Visible dye measures and measures from competing technology	Measurement validation to within *+/- 25%*
5	Accuracy of water flux measurements	Measures from FRPFM and comparative technologies	Measurement validation to within *+/- 25%*
6	Accuracy of contaminant flux measurements	Measures from FRPFM and comparative technologies	Measurement validation to within *+/- 25%*
Qualitative Performance Objectives			
7	Ease of use	Operator acceptance	Field technicians able to effectively take measurements
8	Acceptability of sample analysis	Sample analysis evaluated by external lab	Environmental laboratory acceptance

The FRPFM provides measures of discrete fracture properties (e.g., dip and azimuth) and flux only at the surface of the borehole and not beyond. That is, the FRPFM does not provide measures of fracture properties and fluxes between boreholes; however, estimates for these properties can be obtained using geostatistical models and FRPFM data (Acar et al., 2013).

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4.0 SITE DESCRIPTION

Over the duration of this project, a total of 18 FRPFM deployments were performed at two sites: the Guelph Tool Site (GTS) in Ontario, Canada, and the former Naval Air Warfare Center (NAWC) in West Trenton, New Jersey. Both sites had previously existing networks of well characterized fractured frock wells.

4.1 GUELPH TOOL SITE

4.1.1 GTS: SITE LOCATION AND HISTORY

Guelph Tool Inc. is an automotive parts manufacturing company in the City of Guelph that overlies known TCE contamination in the underlying dolostone aquifer. The criteria used in selecting the GTS were the following:

a. The site has an excellent existing infrastructure to support the demonstration.

b. The site is well-characterized.

c. The site has several well-characterized shallow boreholes in fracture rock (dolostone) of high bulk conductivity.

d. The site has rock fractures that range from visually undetectable (<1 mm) to large apertures (>1 mm).

e. The site has chlorinated solvent contamination.

f. The site has natural-gradient flow conditions.

The GTS is located ~1 mile from the G360 Centre for Applied Groundwater Research at the University of Guelph in Guelph, Ontario. Dr. Parker (one of the project Principal Investigators [PI]) is the director of G360. The site's proximity to G360 and on-site infrastructure enabled the research team to demonstrate detailed characterization of fracture flux variations in multiple well-characterized boreholes. In addition, Dr. Parker's group performed high resolution temperature profiling that enabled the team to demonstrate that the FRPFM detects flow in fractures that are not detectable using optical or acoustic techniques.

4.1.2 GTS: SITE GEOLOGY/HYDROLOGY

The bedrock in the Guelph area corresponds to Paleozoic sedimentary rocks of Middle Silurian age. In the vicinity of the GTS, these are the dolostones of the Guelph Formation, which are underlain by dolostones of the Amabel Formation.

Flow within the bedrock is expected to be predominantly to the south and east, based on limited water level data. The permeability of the Guelph Amabel aquifer is due primarily to the chemical dissolution of dolostone along fractures and bedding planes. The permeability is variable due to the large differences in opening sizes and patterns caused by fracturing. Due to weathering processes, the upper 5 meters of the aquifer is generally the most permeable.

4.1.3 GTS: CONTAMINANT DISTRIBUTION

The contamination at the GTS occurs in a small area and at shallow depths and offers opportunities for examining the internal source zone and plume characteristics in great detail. Transects defining the general boundaries of the source zone and plume are illustrated in Figure 4.

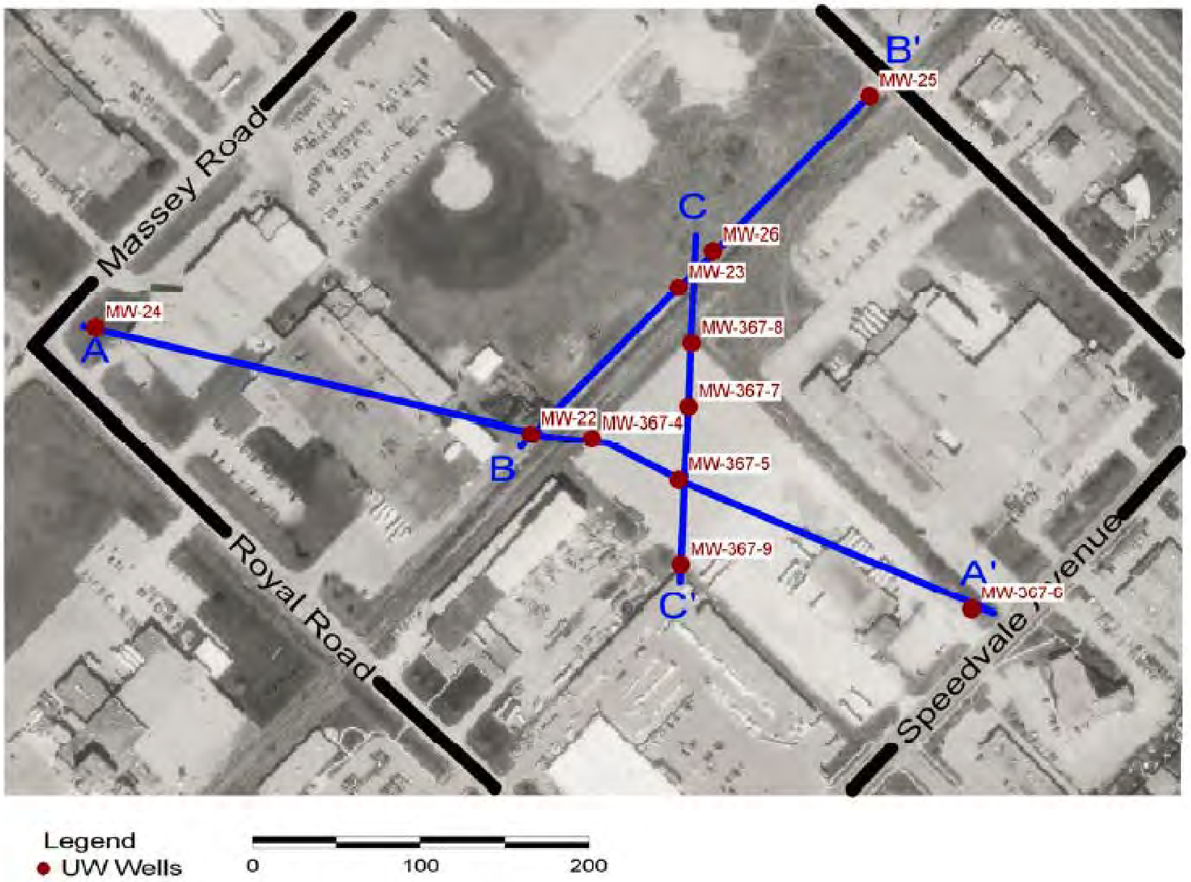


Figure 4. Transects defining the general boundaries of the source zone and plume.

4.2 NAVAL AIR WARFARE CENTER

4.2.1 NAWC: SITE LOCATION AND HISTORY

The NAWC site (Figure 5) is a 60 acre facility located in West Trenton, New Jersey. The NAWC served as a Naval testing facility for aircraft jet engines from the 1950s to 1994. During its operation, TCE was used for its properties of heat exchange in testing aircraft engines under various conditions of temperature and pressure. The handling and disposal of TCE at the site resulted in two source areas of TCE contamination; identified as Site 1 and Site 3 (Figure 5). Site 1 was the area where TCE was stored and handled, and where TCE was spilled or leaked onto the ground. Site 3 consists of a former wastewater lagoon, which was a sludge disposal area and received waste water containing dissolved TCE (Strategic Environmental Research and Development Program [SERDP] project ER-1555; Shapiro, 2008).

The NAWC site provided the challenges of demonstrating the FRPFM in fractured bedded mudstones under induced hydraulic conditions (active pumping). The criteria used in selecting the former NAWC site for field demonstration were the following:

a. The site has an excellent existing infrastructure to support the demonstration.

b. The site is well-characterized.

c. The site has several well-characterized shallow boreholes in fracture rock of very low to high bulk conductivity.

d. The site has rock fractures that range from nonexistent to large apertures (>1 mm).

e. The site has existing fractured rock data on fracture frequency and fracture length distributions gathered from an exposed outcrop.

f. The site has ongoing SERDP-supported activities that can be leveraged.

g. The site has chlorinated solvent contamination.

h. The site has induced-gradient flow conditions.

4.2.2 NAWC: SITE GEOLOGY/HYDROLOGY

The NAWC site (Figure 5) lies on the bedded, fractured sedimentary rocks of the Newark Basin. Soil and weathered rock cover the site to a depth of approximately 15 feet (ft). The water table varies from 5 to 15 ft below land surface over the site. The underlying competent rocks are primarily mudstones and sandstones of the Lockatong and Stockton Formations. The formations generally dip from 20 to 50 degrees toward the north northwest (NNW), and are separated from each other by a near-vertical fault zone (Shapiro, 2008).

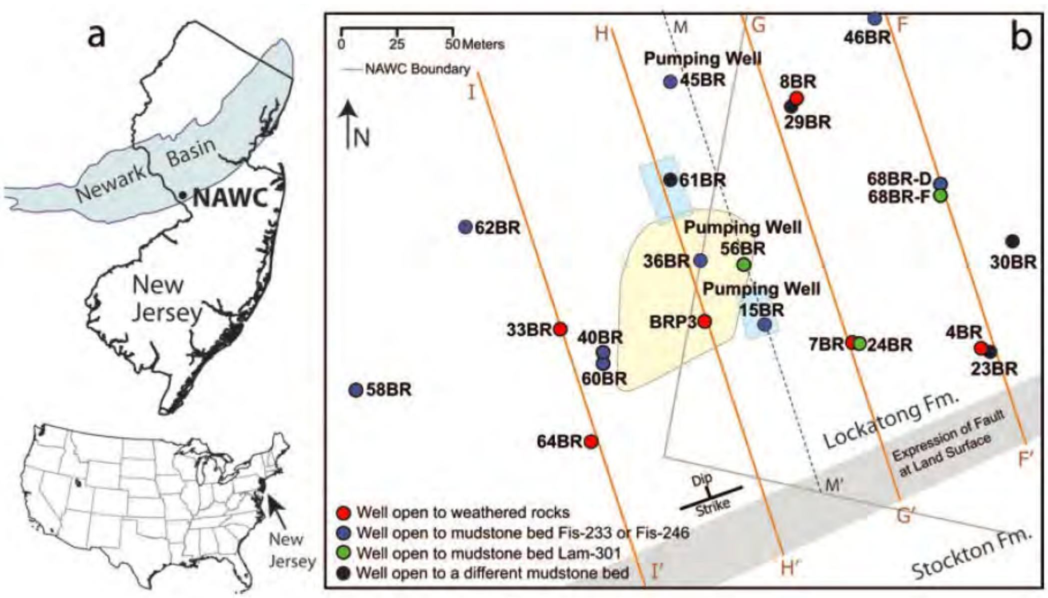


Figure 5. The NAWC site.
(a) Location of the former NAWC site in West Trenton, NJ. (b) Plan view of NAWC site showing locations of pumping and monitoring wells. (Tiedeman et al, 2010).

4.2.3 NAWC: CONTAMINANT DISTRIBUTION

Concentrations of TCE, DCE, and VC have been detected to depths of approximately 200 ft. Because DCE and VC were not independently used at the NAWC, the presence of DCE and VC implies the presence of microbial degradation of TCE to its daughter products. Coring in the bedrock during the first year of activities under SERDP project ER-1555 detected the presence of free-phase TCE and groundwater at concentrations as high as about 100,000 micrograms per liter (µg/L). Samples from rock cores collected showed that the upper part of the bedrock (approximately the top 10 meters of bedrock) has uniform, high concentrations of TCE in the pore fluid of the rock matrix. At greater depths in bedrock, however, TCE concentrations in the pore fluid of the rock matrix are highest near the bedding plane parting fractures. Due to the high concentrations of TCE in fractures, dissolved-phase TCE, DCE, and VC have diffused from fractures into the primary porosity of the sedimentary rock. Because the permeability of the intact rock is many orders of magnitude less than the permeability of the fractures, groundwater in the primary porosity of the rock is not readily accessible to groundwater flow, and diffusion is the primary process controlling the migration of TCE from the intact rock back into the permeable fractures. The back-diffusion is believed to be responsible for the persistently high concentrations of TCE, DCE, and VC detected at the pumping wells at the NAWC. Interpreted concentration contours define the general boundaries of source zones and plumes are illustrated in Figure 6 (Shapiro, 2008).

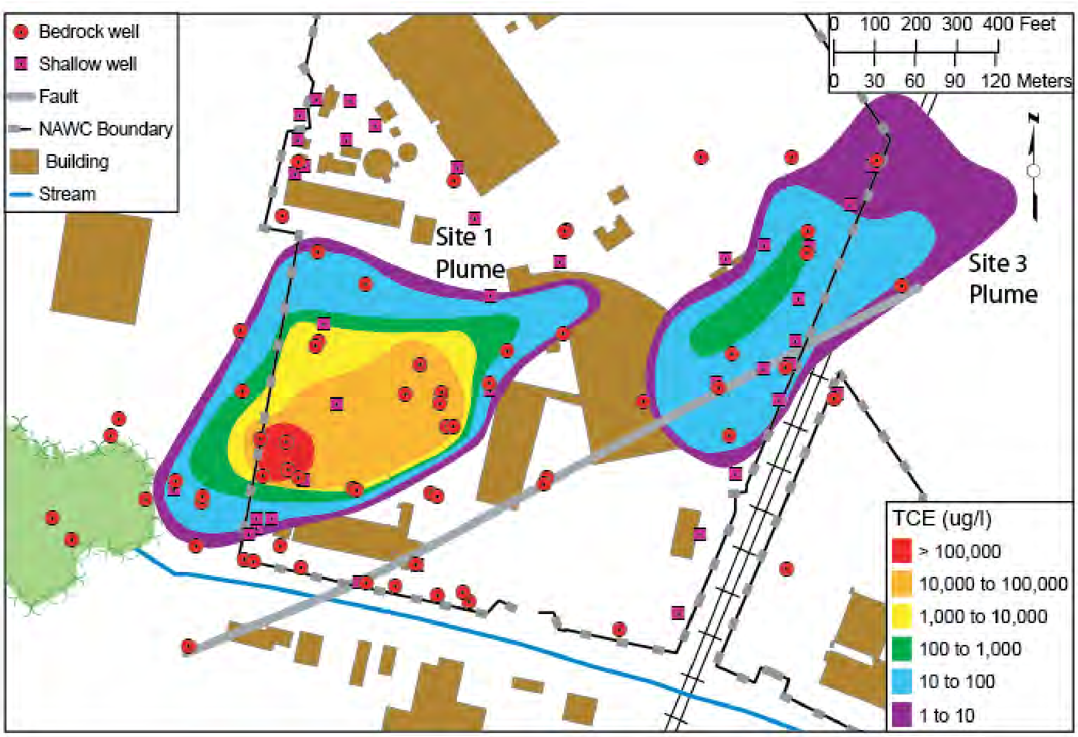


Figure 6. The location of Site 1 and Site 3 TCE plumes interpreted at a depth of 100 ft below land surface at the NAWC, West Trenton, NJ in May 2004.
(Shapiro, 2008)

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

In this demonstration the FRPFM was tested under ambient and induced flow conditions in well-characterized boreholes in both fractured mudstone and dolostone. Repeated flux measurements were taken over regular depth intervals for comparison to competing technologies. Borehole dilution (BHD) tests were conducted over the same depth intervals for validation of flux measurements. To know in advance at what depth intervals to conduct FRPFM testing, selected boreholes were characterized based upon the extent to which data existed on:

1) Location and orientation of visible fractures;
2) Location of flowing fractures under ambient conditions; and,
3) Fractured rock transmissivity at a regular 0.3 to 1.5 meter depth interval.

Thus, the experimental design involved testing the FRPFM performance over multiple 1.0 meter intervals using existing characterization data to guide testing and in addition generate new data from the use of competitive technologies. Given the estimated locations of flowing fractures from high resolution temperature profiling (HRTP), it was feasible to directly assess FRPFM performance under ambient conditions with respect to:

1) Detecting the location of flowing fractures using visible tracers (compared to detection by HRTP);
2) Measuring active fracture orientation using visible tracers (compared to optical detection methods);
3) Measuring water flux at discrete intervals (compared to BHD tests);
4) Measuring TCE and DCE fluxes at discrete intervals (compared to calculated fluxes from TCE and DCE concentrations and measured water flux by BHD tests); and,
5) Measuring active fracture flow direction as indicated by the elution of a visible tracer at locations of active fractures (compared to HRTP measurements).

The fundamental virtue of this basic field demonstration design was the repetitive testing of the FRPFM against competing technologies in one or more well-characterized boreholes in a fractured mudstone and dolostone, thus producing data that can be subjected to rigorous statistical analysis.

5.2 BASELINE CHARACTERIZATION

It is prudent to anticipate that the FRPFM will typically be deployed in deep fractured rock wells or in deep wells screened in fractured rock or unconsolidated materials. To achieve cost-efficiencies in characterizing rock wells, FRPFM deployments will likely follow after other characterization tools (e.g., high resolution temperature logging [Pehme et al., 2007]; contaminant profiling [Sterling et al., 2005]; hydrophysical logging [Wilson et al., 2001]; K-profiling or hydraulic conductivity profiling using a FLUTe™ [Keller et al., 2007], etc.) have been used to locate contaminated fractures and/or fractures believed to conduct flows under

closed-hole conditions. Thus, if the FRPFM demonstration were being conducted on a new borehole, baseline characterization would include the following:

1) Measuring groundwater levels;
2) Measuring contaminant concentrations;
3) Conducting high resolution temperature logging in a FLUTe™ (closed hole conditions) to detect locations of flow fractures;
4) Conducting a down hole optical survey of visible fractures;
5) Analyzing rock cores for fractures or zones of contamination; and possibly,
6) Conducting targeted straddle packer tests Fracture hydraulic conductivity or hydraulic conductivity profiling using a FLUTe™ (Keller et al., 2007).

Because baseline characterization activities 3-6 were previously completed at both GTS and NAWC in multiple wells, measurement of water levels and contaminant concentrations were the two characterizations that were necessary prior to and during FRPFM field testing.

5.2.1 LABORATORY STUDY RESULTS

The intent of this phase of work was to select: 1) resident tracers and sorbent appropriate for the target contaminants and fracture flow conditions; 2) an appropriate visual tracer (dye) and fabric for visual indication of flowing fractures; and 3) to perform initial prototype design and deployment testing to prepare for field-scale testing.

Each stage of lab work had multiple tasks, and portions of each stage were performed in parallel to determine the best individual device components for specific purposes (i.e., the best combination of dyes and fabric to provide visual indication of flowing fracture, and the best combination of sorbents and resident tracers for measuring water flow/flux within fractures). Once tested, the individual components were assembled for prototype testing using two different physical flow simulators (fracture flow simulator and large three-dimensional aquifer box). The flow tests were used to evaluate FRPFM performance under controlled flow conditions, and to compare results from competing open- and closed-hole technologies. A third and final stage of lab testing was performed in a full-scale mock borehole (4-inch diameter polyvinyl chloride [PVC] casing 36 ft deep) to simulate field deployment conditions in order to assess field-scale installation issues and develop optimal installation procedures in preparation for field tests. Between each stage of testing the FRPFM prototype was modified and scaled-up to prepare for field testing. More detailed discussion of lab procedures and results is provided in section 5.3 of the project Final Report.

5.3 FIELD TESTING

Over the duration of the project, 22 FRPFM deployments and 35 modified BHD tests were performed at two sites: GTS in Ontario, Canada, and the former NAWC in West Trenton, New Jersey, both of which had previously existing networks of well characterized fractured frock wells. The field demonstration tests were performed in a sequential fashion, progressively testing individual components of the FRPFM technology while incrementally incorporating newer

components and evaluating field deployment challenges in order to determine optimal deployment mechanisms and strategies. Gantt charts showing the schedule of field activities performed at GTS and NAWC are provided in Tables 2 and 3, respectively.

Table 2. Scheduled activities for FRPFM demonstration at GTS.

Field Testing: GTS					
Activity	Year 2008-2012				
	2008	2009	2010	2011	2012
Startup	x				
Directional Flow Survey (HRTP/TVP)	x	x			
FRPFM deployment, extraction, and sampling	x	x	x	x	x
BHD Testing			x	x	x
Demobilization					x

TVP = temperature vector probe

Table 3. Scheduled activities for FRPFM demonstration at the NAWC site.

Field Testing: NAWC		
Activity	Year 2012-2013	
	2012	2013
Startup—mobilization	x	
Directional Flow Survey (HRTP/TVP)	x	
FRPFM deployment, extraction, and sampling	x	x
BHD Testing	x	x
Demobilization		x

In parallel with laboratory testing and development, during 2008 and 2009, collaborators at the University of Guelph performed directional flow surveys at GTS and provided HRTPs for all potential wells. Then, the initial four FRPFM field deployments were performed with the primary intent of evaluating the challenges of field-scale deployment. These early tests only incorporated the visual tracer component of the FRPFM technology suite. These early field tests experienced limited success with visual tracers on a cotton visual indication sock. Visual indication of potential fractures were observed and confirmed with acoustic and optical televiewer (ATV and OTV). More importantly, these tests provided invaluable information with regard to deployment mechanisms that were directly implemented in the design of the next stage of FRPFM field prototypes tested in 2010.

All field tests with quantifiable results are summarized in the matrix of results (Table 4), which provides a general outline of all data collected by FRPFM and comparative technologies. As mentioned above, the initial four field deployments were used to evaluate field-scale deployment challenges and are not included in Table 4. There were also two tests performed to completion (Tests E and M) that are not listed in the table. These tests did not provide quantifiable results due to vandalism and damaged equipment. As such, there are 16 tests listed in the table that provide comparison between FRPFM and three comparative technologies—ATV/OTV, HRTP/TVP, and BHD tests.

Table 4. Matrix of test results—provides general summary of data collected by FRPFM and comparative technology for all field tests.

	Test	Comparative Technology							FRPFM						
		ATV/OTV		HRTP		BHD			Visual Tracer				Alcohol Tracer	FRPM Sorbent	
		Fracture Depth	Fracture Orient	Fracture Flow Depth	Flow Direction	Specific Discharge	Contaminant Flux	Contaminant Flux Concentration	Fracture Depth	Fracture Orient	Specific Discharge	Flow Direction	Specific Discharge	Contaminant Flux	Contaminant Flux Concentration
GTS	A	X	X	X	X	NA	NA	NA	X	X	X	NA	X	NA	NA
	B	X	X	X	X	NA	NA	NA	X	X	X	X	X	NA	NA
	C	X	X	X	X	NA	NA	NA	NA	NA	X	NA	X	NA	NA
	D	X	X	X	X	NA	NA	NA	X	X	X	X	X	NA	NA
	F	X	X	X	X	NA	NA	NA	X	X	X	X	NA	NA	NA
	G	X	X	X	X	NA	NA	NA	X	X	X	X	X	X	X
	H	X	X	X	X	NA	NA	NA	NA	NA	NA	NA	X	X	X
	I	X	X	X	X	X	X	X	NA	NA	NA	NA	X	X	X
	L	X	X	X	X	X	X	X	NA	NA	NA	NA	X	X	X
NAWC	J	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	K	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	N	X	X	X	X	X	X	X	X	X	NA	NA	X	X	X
	O	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	P	X	X	X	X	X	NA	NA	X	X	NA	NA	X	X	X
	Q	X	X	X	X	X	NA	NA	X	X	NA	NA	X	X	X
	R	X	X	X	X	X	X	X	X	X	NA	X	X	X	X

X – quantifiable results
NA – not available

During 2010, five FRPFM field deployments were performed at the Guelph Tool site. The target zones for FRPFM interrogation were determined based upon pre-existing geophysics data (ATV/OTV) and closed-hole HRTP/TVP profiles used to indicate the presence of flow within the borehole. The first FRPFM test of 2010 incorporated two components of the FRPFM technology suite: 1) internal alcohol tracers on a new sorbent media (activated carbon felt) that was selected specifically for fracture rock applications based upon extensive laboratory testing; and 2) improved visual tracer sock now composed of a nylon-spandex blend (again, specifically selected for fracture rock applications based upon extensive laboratory testing). The internal tracers provide a direct measure of volumetric water flux (specific discharge) through the FRPFM, while the visual tracer provides indication of the presence, spatial distribution, and orientation of flowing fractures along with the direction of groundwater flow and an independent measure of water flux. Subsequent field tests during 2010 incrementally added new components to each subsequent FRPFM field prototype. Tests were performed incorporating a stainless steel shield used to encapsulate the FRPFM during downward deployment and upward retrieval within the borehole. The shield serves two purposes: 1) it physically protects the integrity of the visual tracer sock and underlying activated carbon felt by preventing contact with fracture rock face of borehole; and 2) it precludes internal tracer loss due to vertical flow of water through the device during deployment and retrieval. The final phase of testing during 2010 incorporated an accelerometer on the base of the FRPFM assembly in order to record the orientation of the device with regard to magnetic north during deployment. This allows for evaluation of the direction of flow within the FRPFM interrogation zone. With the inclusion of the accelerometer, the complete suite of FRPFM technologies had been assembled and tested at the field scale.

During 2011, three FRPFM field deployments were performed along with three modified BHD tests at GTS. The intent for this phase of testing was to evaluate the FRPFM capabilities for quantifying contaminant flux, and to validate the FRPFM values for water flux and contaminant flux with independent measures obtained using modified BHD tests.

During 2012, field demonstration efforts were expanded to include tests running in parallel at both GTS and NAWC in New Jersey. A total of five FRPFM deployments were performed, along with one FRPFM push-pull test and 16 BHD tests.

The final phase of field testing was performed in 2013 at the NAWC site. A total of five FRPFM deployments were performed along with 16 modified BHD tests.

The outcome of the combined results from all of the field tests is to demonstrate that the FRPFM provides direct, high-resolution, simultaneous measure of six data types with regard to actively flowing fractures. The data types correspond to the quantitative performance objectives outlined in Table 1: 1) detection of flowing fractures, 2) fracture location (depth), 3) fracture orientation, 4) fracture flow direction, 5) groundwater flux (specific discharge), and 6) contaminant mass flux.

5.4 SAMPLING METHODS

The objective of the sampling plan for this study was to acquire sufficient data to validate FRPFM technology performance in the field and allow regulatory agencies and managers to evaluate the innovative nature of the technology. Because the FRPFM provides time integrated

measures of both water and contaminant fluxes, temporal variations in flux are not a concern. However, spatial variations in flux can be significant. The visible tracers used on the FRPFM provide an indication of where sorbent sampling is needed to quantify water and contaminant fluxes in active fractures. Using visual tracer results to inform sorbent sampling allows for proper evaluation of spatial variations in both water and contaminant fluxes.

Sample Collection. Two types of samples were collected during this study: ground water samples, and sorbent samples from FRPFM. Sampling methods and sample handling procedures are discussed in detail in Section 5.6 of the project Final Report.

5.5 SAMPLING RESULTS

During 2010, five FRPFM field deployments were performed at GTS (Tests A, B, C, D, and E). The target zones for FRPFM interrogation were determined based upon pre-existing geophysics data and closed-hole high resolution temperature profiles used to indicate the presence of flow within the borehole. The objectives of these early tests were to: 1) test the capability of the FRPFM to identify flowing features within fractured rock systems; and 2) provide estimates for flow direction. It should be noted that the deployment depth for all tests is referenced to the center of the 1-meter FRPFM interrogation zone. As such, there is 0.5 meter (1.64 ft) of interrogation above and below the listed deployment depth.

The first FRPFM test (Test A) was performed in well MW-26 with deployment duration of 4 days at a depth of 13.30 meters below ground surface (bgs) (43.64 ft-bgs). This phase of field tests incorporated two components of the FRPFM technology suite: 1) internal alcohol tracers on a new sorbent media (activated carbon felt) that was selected specifically for fractured rock applications based upon extensive laboratory testing; and 2) improved visual tracer sock now composed of a nylon-spandex blend (again, specifically selected for fracture rock applications based upon extensive laboratory testing). The elution of internal tracers provide a direct measure of volumetric water flux (specific discharge) through the FRPFM, while the visual tracer provides indication of the presence, spatial distribution, and orientation of flowing fractures along with the direction of groundwater flow and an independent measure of water flux. When the initial FRPFM prototype was retrieved, imaged, and sampled there were faint visual indications of a three potential flowing vertical and diagonal fractures with centroids at 13.29, 13.35, and 13.41 meters bgs. ATV-OTV logs indicated horizontal features at 13.43 and 13.72 meters bgs, and HRTP had indicated flow at 13.3 meters bgs. Analysis of the FRPFM internal alcohol tracers indicated a flow per unit width of 60 square centimeters per day (cm^2/day), while evaluation of the apparent aperture and length of the individual visual dye features indicated a flow per unit width of 76 cm^2/day. There was no quantifiable contaminant flux at this depth. Flux data for all tests are summarized in Tables 5 and 6. Table 5 summarizes results for comparative technologies (HRTP/TVP and BHD) while Table 6 summarizes results for FRPFM technologies (visual tracers, alcohol tracers and sorbent).

Table 5. Matrix of flux results for comparative technologies (HRTP/TVP and BHD).

	Test	Well ID	Deployment Depth (m-bgs)	Deployment Depth (ft-bgs)	Comparative Technology								
					HRTP/TVP	BHD							
					Flow Direction	Specific Discharge (cm/day)	Flow Per Unit Width (cm^2/day)	TCE Flux (μg/m^2/day)	DCE Flux (μg/m^2/day)	TCE Mass Discharge Per Length of Fracture (μg/m/day)	DCE Mass Discharge Per Length of Fracture (μg/m/day)	TCE Flux-Average Concentration (μg/L)	DCE Flux-Average Concentration (μg/L)
GTS	A	MW-26	13.30	43.64	SSE	NA	NA	NA	NA	NA	NA	NA	NA
GTS	B	MW-26	13.40	43.96	SSE	NA	NA	NA	NA	NA	NA	NA	NA
GTS	C	MW-26	6.48	21.25	SSE	NA	NA	NA	NA	NA	NA	NA	NA
GTS	D	MW-25	7.93	26.00	SSE	NA	NA	NA	NA	NA	NA	NA	NA
GTS	F	MW-367-8	10.32	33.86	SSE	NA	NA	NA	NA	NA	V	NA	NA
GTS	G	MW-367-8	10.32	33.86	SSE	NA	NA	NA	NA	NA	NA	NA	NA
GTS	H	MW-367-8	10.42	34.19	SSE	NA	NA	106.2	NA	NA	NA	11.805	NA
GTS	I	MW-367-9	27.73	90.99	SSE	0.44	47.5	9.5	9.944	10.3	10.8	2.16	2.26
GTS	L	MW-367-9	27.73	90.99	SSE	0.91	93.7	19.656	20.566	21	22.2	2.16	2.26
NAWC	J	68-BR	28.96	95.00	WNW	2.9	292	116,870	48,343	116,870	48,343	4030	1667
NAWC	K	68-BR	29.46	96.64	WNW	NA	NA	NA	NA	171,720	86,832	795	402
NAWC	N	68-BR	28.99	95.12	WNW	3.2	318	38,400	23,968	40,545	24,486	1200	749
NAWC	O	68-BR	28.99	95.12	WNW	3.4	318	148,802	63,086	40,576	24,505	4442	1883
NAWC	P	68-BR	28.53	93.62	WNW	3.8	NA	147,524	48,679	NA	NA	4610	1521
NAWC	Q	68-BR	29.45	96.62	WNW	2.3	NA	155,791	40,803	NA	NA	8200	2148
NAWC	R	68-BR	40.73	133.62	WSW	1.3	NA	69,634	43,773	NA	NA	5483	3447

X – quantifiable results
NA – not available

Table 6. Matrix of flux results for FRPFM technologies (visual tracer, alcohol tracer, and sorbent).

	Test	Well ID	Deployment Depth (m-bgs)	Deployment Depth (ft-bgs)	FRPFM										
					Visual Tracer			Alcohol Tracer		FRPFM Sorbent					
					Specific Discharge (cm/day)	Flow Per Unit Width (cm^2/day)	Flow Direction	Specific Discharge (cm/day)	Flow Per Unit Width (cm^2/day)	TCE Flux (μg/m^2/day)	DCE Flux (μg/m^2/day)	TCE Mass Discharge Per Length of Fracture (μg/m/day)	DCE Mass Discharge Per Length of Fracture (μg/m/day)	TCE Flux-Average Concentration (μg/L)	DCE Flux-Average Concentration (μg/L)
GTS	A	MW-26	13.30	43.64	NA	76	NA	NA	60	NA	NA	NA	NA	NA	NA
GTS	B	MW-26	13.40	43.96	NA	49	W (286E)	NA	56	NA	NA	NA	NA	NA	NA
GTS	C	MW-26	6.48	21.25	NA	NA	NA	33	NA	NA	NA	NA	NA	NA	NA
GTS	D	MW-25	7.93	26.00	NA	8.3	SW (242E)	NA	10.8	NA	NA	NA	NA	NA	NA
GTS	F	MW-367-8	10.32	33.86	1.28	101	S (177E)	NA	NA	NA	NA	NA	V	NA	NA
GTS	G	MW-367-8	10.32	33.86	NA	NA	S (184E)	10.3	1432	1514	NA	1378	NA	16.5	NA
GTS	H	MW-367-8	10.42	34.19	NA	NA	NA	1.5	123	172	NA	137	NA	11.2	NA
GTS	I	MW-367-9	27.73	90.99	NA	NA	NA	0.4	41	16.1	18.0	16.6	18.5	4	4.5
GTS	L	MW-367-9	27.73	90.99	NA	NA	NA	0.9	92	8.5	13.6	8.7	14.0	0.9	1.4
NAWC	J	68-BR	28.96	95.00	2.1	206	WSW (245E)	2.5	252	105,116	57,116	105,116	57,116	4179	2287
NAWC	K	68-BR	29.46	96.64	24	2400	WSW (248E)	21.6	2159	161,646	83,503	161,646	83,503	751	386
NAWC	N	68-BR	28.99	95.12	NA	NA	NA	3.2	323	50,091	27,558	50,091	27,558	1466	807
NAWC	O	68-BR	28.99	95.12	3.9	390	SSW (199E)	3.8	360	148,849	55,647	141,407	52,865	3771	1410
NAWC	P	68-BR	28.53	93.62	NA	NA	NA	3.3	317	144,475	52,865	137,251	50,222	4247	1554
NAWC	Q	68-BR	29.45	96.62	NA	NA	ESE (113E)	2.1	199	145,523	51,888	138,247	49,293	6639	2367
NAWC	R	68-BR	40.73	133.62	NA	NA	WNW (288E)	1.0	98	23,279	33,072	22,115	31,418	2182	3100

X – quantifiable results
NA – not available

Subsequent field tests in 2010 incrementally added new components to each FRPFM field prototype that was deployed. The next component that was incorporated was an accelerometer on the base of the FRPFM assembly in order to record the orientation of the device with regard to magnetic north during deployment. This allows for evaluation of the direction of flow within the FRPFM interrogation zone. Test B was the first phase of testing that incorporated the accelerometer and was performed in well MW-26 with deployment duration of 4 days at a depth of 13.40 m-bgs (43.96 ft-bgs). When the FRPFM was retrieved, imaged, and sampled there were visual indications of two vertical flowing features. The upper feature was 21 cm long with a centroid at 13.23 m-bgs (43.41 ft-bgs) and an apparent aperture of 0.33 cm, while the lower feature was 10 cm long with a centroid at 13.92 m-bgs (45.67 ft-bgs) and an apparent aperture of 0.93 cm. The location of the upper feature corresponded with a potential vertical fracture noted in the acoustic televiewer data log possibly connecting two apparent horizontal fractures. FRPFM alcohol tracers indicated an average flow per unit width of 56 cm^2/day while evaluation of visual dye features indicated an average flow per unit width of 49 cm^2/day (Table 6). There was no quantifiable contaminant flux at this depth. Both of the visual features were on the same face of the FRPFM and were essentially collinear at approximately 106E from north (with a reported accuracy of 0.5 to 2.0 degrees root mean squared error for the accelerometer). As discussed in section 5.3.4, the visual features on the FRPFM sock indicate where flow has entered the device. As such, the inferred flow direction is offset by 180E, and the estimated groundwater flow direction within the FRPFM interrogation zone during Test B was 286E (west).

Test C was the first test performed that incorporated a stainless steel shield that was designed to encapsulate the FRPFM during deployment and retrieval within the borehole. The shield serves two purposes: 1) it physically protects the integrity of the visual tracer sock and underlying activated carbon felt by preventing contact with the fracture rock face of the borehole; and 2) it precludes internal tracer loss due to vertical flow of water through the device during deployment and retrieval. Test C was performed in the highly weathered upper portion of MW26 with deployment duration of 5 days at a depth of 6.48 m-bgs (21.25 ft-bgs). The rock in this zone is unconsolidated with large voids and sharp edges. During 2009, preliminary FRPFM tests in this zone experienced both packer and visual sock failure due to contact with the sharp rock face. Once the shield was incorporated for Test C, FRPFM deployment, retrieval, and sampling all went well with no complications. Imagery of the visual indication sock showed significant washout on one face of the FRPFM with little to no dye remaining in the active flow zone. But, above and below the flow zone there was still tracer visible on the sock and more importantly, on the back (down gradient) side of the FRPFM there was still visual tracer present on the sock. All of these conditions correspond with expected results previously validated using the large scale aquifer box with high contrast flow zones at the University of Florida Coastal Laboratory (as discussed in section 5.3.4). Based upon analysis of internal alcohol tracers, the specific discharge within the washout zone was 33 cm/day (Table 6). There was no quantifiable contaminant flux at this depth. Test B and C were performed in parallel with two separate FRPFM prototypes. The prototype used for test C did not incorporate an accelerometer and as such the flow direction was not estimated.

Test D was performed in well MW25 with a deployment duration of 5 days at a depth of 7.93 m-bgs (26 ft-bgs). When retrieved there were visual indications of three vertical flowing features

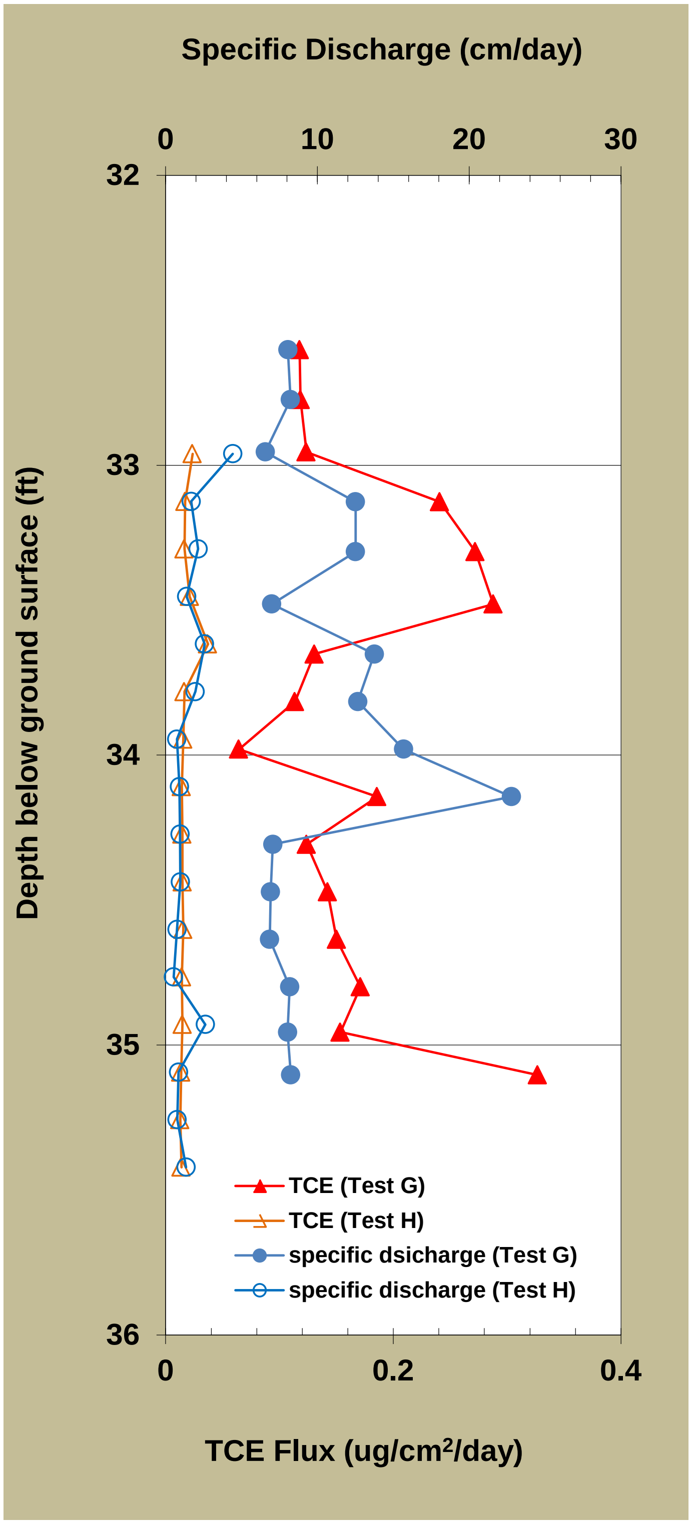
with centroids located at 7.63 m-bgs (25.05 ft-bgs), 7.88 m-bgs (25.85 ft-bgs), and 8.04 m-bgs (22.39 ft-bgs). The upper feature was 20 cm long with an apparent aperture of 0.17 cm, the middle feature was 4.5 cm long with an apparent aperture of 0.05 cm, and the bottom feature was 10 cm long with an apparent aperture of 0.35 cm. FRPFM alcohol tracers indicated an average flow per unit width of 10.8 cm^2/day while evaluation of visual dye features indicated an average flow per unit width of 8.3 cm^2/day (Table 6). There was no quantifiable contaminant flux at this depth. The three centroids of the visual features were located at 35.6E, 66.3E and 84.4E from north with inferred flow directions of 215.6°, 246.3°, and 264.4°, respectively. As such, the estimated general direction of groundwater flow within the FRPFM interrogation zone during Test D was 242° (southwest).

Test E was run to completion, and the FRPFM was successfully retrieved. However, it was determined that the packer assembly had developed a leak during the deployment and the interrogation zone had not been vertically sealed for the duration of the test compromising the FRPFM results. As such, no data is reported but the test E designation is still recorded for continuity of discussion.

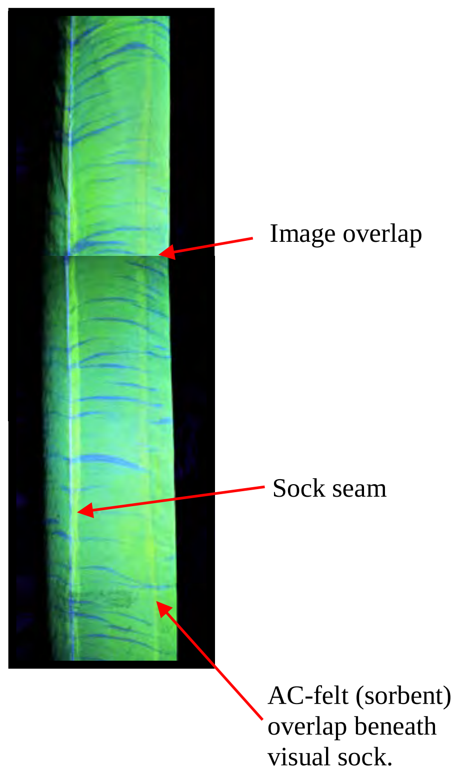
During 2011, three FRPFM field deployments were completed. The intent for this phase of testing was to evaluate the FRPFM capabilities for quantifying contaminant flux. A new well was selected for this phase of testing (MW-367-8) as it was anticipated to be along the periphery of the longitudinal axis of the contaminant plume.

Test F was performed in well MW-367-8 with a deployment duration of 10 days at a depth of 10.32 m-bgs (33.86 ft-bgs). When retrieved, there were visual indications of 56 discrete horizontal flowing features distributed along the device (Figure 7). Evaluation of the visual features indicated a flow per unit width of 101 cm^2/day corresponding to a specific discharge of 1.28 cm/day over the interrogation zone (Table 6). Unfortunately, all samples of the FRPFM sorbent were destroyed during shipping from Canada to the United States and no analytical analysis of flux was possible. Evaluation of the location of centroids for each of the discrete horizontal features was used to estimate an average groundwater flow direction of 177E (south) (Table 6).

Test G was performed in well MW-367-8 at the same depth as test F (10.32 m-bgs) with a deployment duration of 7 days. When retrieved, imagery indicated significant vertical washout of visual tracers at both the top and bottom of the interrogation zone. It was confirmed that the packers had maintained pressured for the duration of the test and the interrogation zone had been sealed. However, there was significant rainfall prior to and during the test. The visual dye washout zones were all predominantly on the same face of the FRPFM corresponding to an inferred groundwater flow direction of 184E (south). FRPFM alcohol tracers indicated a flow per unit width of 834 cm^2/day with a specific discharge of 10.3 cm/day over the interrogation zone (Table 6 and Figure 7). Analysis of the FRPFM sorbent indicated a TCE mass flux of 1,514 $\mu g/m^2$/day with flux averaged TCE concentration of 16.5 µg/L (Table 6 and Figure 7).



UV image of visual dye sock from Test F



Note: Image is of uninflated FRPFM after retrieval with width (diameter) = 3.2 inches. When deployed, the device was inflated with a diameter of 3.8 inches. As such, the visual features in the image have exaggerated curvature with respect to actual conditions.

Figure 7. Summary of flux measurements and visual results for Tests F, G, and H comparing vertical distribution of water flux (specific discharge), contaminant flux and presence of flowing fractures.

Test H was performed in well MW-367-8 with the deployment depth shifted down 0.1 m to 10.42 m-bgs (34.19 ft-bgs) to avoid a large fracture that had been intercepted by the upper shield packer during tests F and G. Although the packer had not failed during tests F and G, it had shown significant signs of fatigue after test G. The packer was replaced and a deployment was attempted at the same depth (10.32 m-bgs), but the packer ruptured almost immediately. The packer was again replaced and again ruptured during another attempted deployment at 10.32 m-bgs. It was then that the decision was made to shift the deployment depth down by 0.1 m to 10.42 m-bgs (34.19 ft-bgs). At this depth, the FRPFM packers held pressure, and maintained integrity for a deployment duration of 4 days. The 4-day duration was selected due to the relatively high fluxes that had been observed during test G. However, when the FRPFM was retrieved there were minimal visual indications of flow. FRPFM alcohol tracers indicated a flow per unit width of 123 cm^2/day with a specific discharge of 1.5 cm/day over the interrogation zone (Table 6 and Figure 7). Analysis of the FRPFM sorbent indicated a TCE mass flux of 172 µg/m^2/day with flux averaged TCE concentration of 11.2 µg/L (Table 6 and Figure 7).

Figure 7 summarizes results for tests F, G, and H comparing the vertical distribution of water flux (specific discharge) from FRPFM alcohol tracers, contaminant flux from FRPFM sorbent, and FRPFM visual indication of flowing fractures. There was an order of magnitude increase in water and contaminant flux during test G, which can likely be attributed to significant rainfall prior to and during test G.

During 2012, field demonstration efforts were expanded to include tests running in parallel at both GTS and the NAWC site in New Jersey. A total of five FRPFM deployments were performed (two at GTS and three at NAWC), along with one FRPFM push-pull test and 16 BHD tests. The intent of this phase of testing was to evaluate all components of the FRPFM technology suite. The conditions between the two test sites provide a drastic contrast for FRPFM testing. GTS has relatively low aqueous contaminant concentrations (mean flux average TCE concentration = 8.15 µ/L) and experiences relatively low ambient groundwater velocities. NAWC is an active pump and treat site with induced gradient conditions (higher groundwater velocities) and significantly higher contaminant concentrations (mean flux average TCE concentration = 3,319 µ/L).

At GTS, all final tests were performed in a newly selected well (MW-367-9), which was expected to be along the primary longitudinal axis of the contaminant plume resulting in higher contaminant concentrations. The selection of MW-367-9 presented a new challenge, as all previous FRPFM wells had been 4-inch diameter. MW-367-9 is a 6-inch diameter well, requiring construction of new larger diameter FRPFM prototypes. Two new 6-inch FRPFM prototypes were constructed, one for GTS and one for NAWC.

Test I was performed at GTS in MW-367-9. Prior to deployment a series of low flow sampling and BHD tests were performed to select a target FRPFM deployment depth with both quantifiable flow and contaminant flux. The results indicated that there was only one zone that had consistently quantifiable contaminant concentrations (both TCE and DCE) and a target deployment depth of 27.73 m-bgs (90.99 ft-bgs) was selected within this zone. At this depth, BHD results indicated a specific discharge of 0.44 cm/day with TCE and DCE mass flux values of 9.5 µg/m^2/day and 9.9 µg/m^2/day respectively (Table 5) within the 1-meter interrogation zone. As mentioned previously, the BHD probe was constructed to interrogate a 1-meter zone identical to that of the FRPFM. Following BHD tests, FRPFM Test I was completed with a deployment

duration of 39 days at the target depth of 27.73 m-bgs. The 39-day duration was selected due to the low specific discharge values observed during BHD testing. When retrieved, imagery showed little to no visual indications of flow. FRPFM alcohol tracers indicated a specific discharge of 0.4 cm/day over the interrogation zone (Table 6). Analysis of the FRPFM sorbent indicated TCE and DCE mass flux values of 16.1 μg/m^2/day and 18.0 μg/m^2/day respectively (Table 6).

Note: Test L was performed in parallel with Test J and K with Test L at GTS, and Tests J and K at NAWC. For continuity of discussion Test L is discussed next before Tests J and K.

Test L was the final test performed at GTS and was also performed in MW-367-9 at the same deployment depth as Test I. Prior to deployment, another BHD test was performed for comparison to and validation of FRPFM flux measurements. BHD results indicated a specific discharge of 0.91 cm/day with TCE and DCE mass flux values of 19.4 μg/m^2/day and 20.6 μg/m^2/day respectively (Table 5). FRPFM Test L was then completed with a deployment duration of 32 days at the target depth of 27.73 m-bgs. When retrieved, imagery again showed little to no change in visual tracers (similar to Test I). FRPFM alcohol tracers indicated a specific discharge of 0.9 cm/day over the interrogation zone (Table 6). Analysis of the FRPFM sorbent indicated TCE and DCE mass flux values of 8.5 μg/m^2/day and 13.6 μg/m^2/day respectively (Table 6).

All tests at NAWC were performed in a well characterized 6-inch diameter well (68-BR). Prior to FRPFM deployment by the University of Florida, the University of Guelph with assistance from U.S. Geological Survey (USGS) and FLUTe completed ATV/OTV logs of the open hole along with a transmissivity log and HRTP/TVP profiles of the lined hole (closed-hole conditions). The HRTP/TVP results were used to identify five target zones with active flow for potential investigation with FRPFM. The University of Florida then performed a series of low flow sampling and BHD tests to evaluate each of the five HRTP/TVP-identified target zone for quantifiable flow and contaminant flux.

Test J was the first FRPFM test performed at the NAWC site in West Trenton, NJ. Based upon HRTP/TVP logs and BHD results a target depth of 95 ft-bgs was selected for FRPFM deployment. BHD results at this depth had indicated a specific discharge of 2.9 cm/day over the interrogation zone with TCE and DCE mass flux values of 116,870 μg/m^2/day and 48,343 μg/m^2/day respectively (Table 5). Test J was performed with a deployment duration of 9 days at a depth of 95 ft-bgs. When retrieved there were visual indications of 56 discrete horizontal flowing features distributed along the device. The most striking of these features was a large diagonal feature at the bottom of the FRPFM interrogation zone that appeared to correspond precisely with USGS ATV logs at this depth (Figure 8). As discussed in section 5.3.4, visual features on the FRPFM sock indicate where flow has entered the device. As such, the inferred flow direction is offset by 180E. For the case of the visual features shown in Figure 8, flow enters along the eastern face of the FRPFM and exits along the western face. Based upon the location of centroids for all visual features, referenced to the FRPFM accelerometer directional orientation, the inferred general flow direction for Test J was 245E (west south west). Evaluation of the visual features indicated a specific discharge of 2.1 cm/day over the interrogation zone (Table 6). FRPFM alcohol tracers indicated an average specific discharge of 2.5 cm/day over the interrogation zone (Table 6). Analysis of the FRPFM sorbent indicated TCE and DCE mass flux values of 105,116 μg/m^2/day, and 57,116 μg/m^2/day respectively (Table 6).

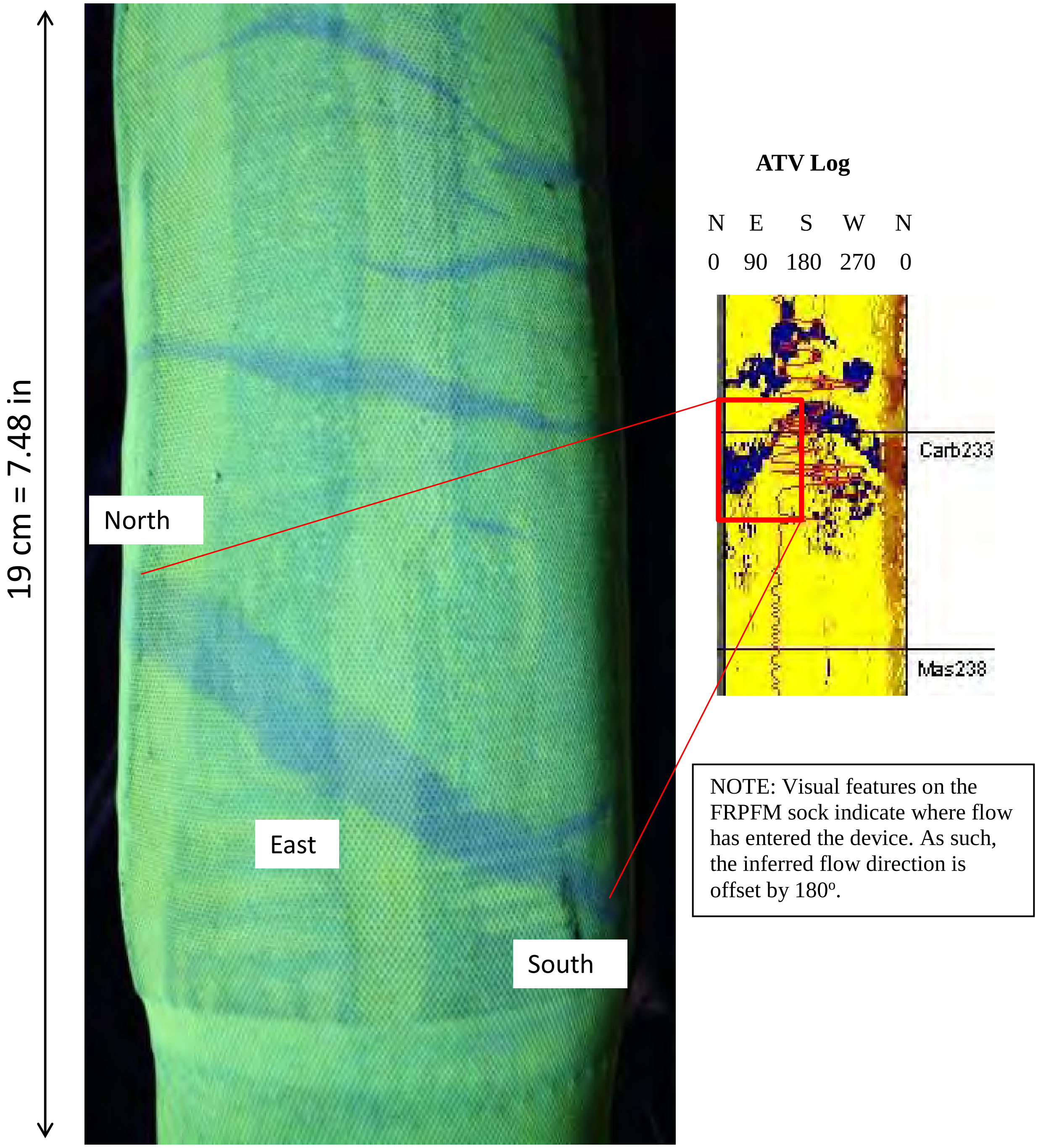


Figure 8. Test J imagery of visual flow indications compared to ATV log at same depth.
NOTE: Imagery is of FRPFM visual indication sock on uninflated device after deployment. In this form the visual features are mirror images of features in ATV/OTV logs.

Test K was performed at NAWC in well 68BR with a deployment duration of 18 hours at a depth of 96.64 ft-bgs. The short deployment duration was selected due to relatively high discharges observed during BHD tests at this depth. BHD results indicated a specific discharge of 21.6 cm/day over the interrogation zone with TCE and DCE mass flux values of 171,720 μg/m^2/day and 86,832 μg/m^2/day, respectively (Table 5). When retrieved, there were visual indications of 80 discrete horizontal flowing features distributed along the device. As part of Test K, improved image analysis techniques were incorporated in order to better evaluate visual features on the FRPFM sock. As part of the new protocol, the FRPFM sock was returned to the laboratory, cut open, and lain flat for image processing. Figure 9 shows a black and white image of a portion of the FRPFM sock with centroids for each individual feature referenced to the FRPFM accelerometer directional orientation. The inferred general flow direction for Test K was 248E (west south west). Evaluation of the visual features indicated a specific discharge of 24 cm/day over the interrogation zone (Table 6). FRPFM alcohol tracers indicated a specific discharge of 21.6 cm/day over the interrogation zone (Table 6). Analysis of FRPFM sorbent indicated TCE and DCE mass flux values of 161,646 μg/m^2/day and 83,503 μg/m^2/day, respectively (Table 6).

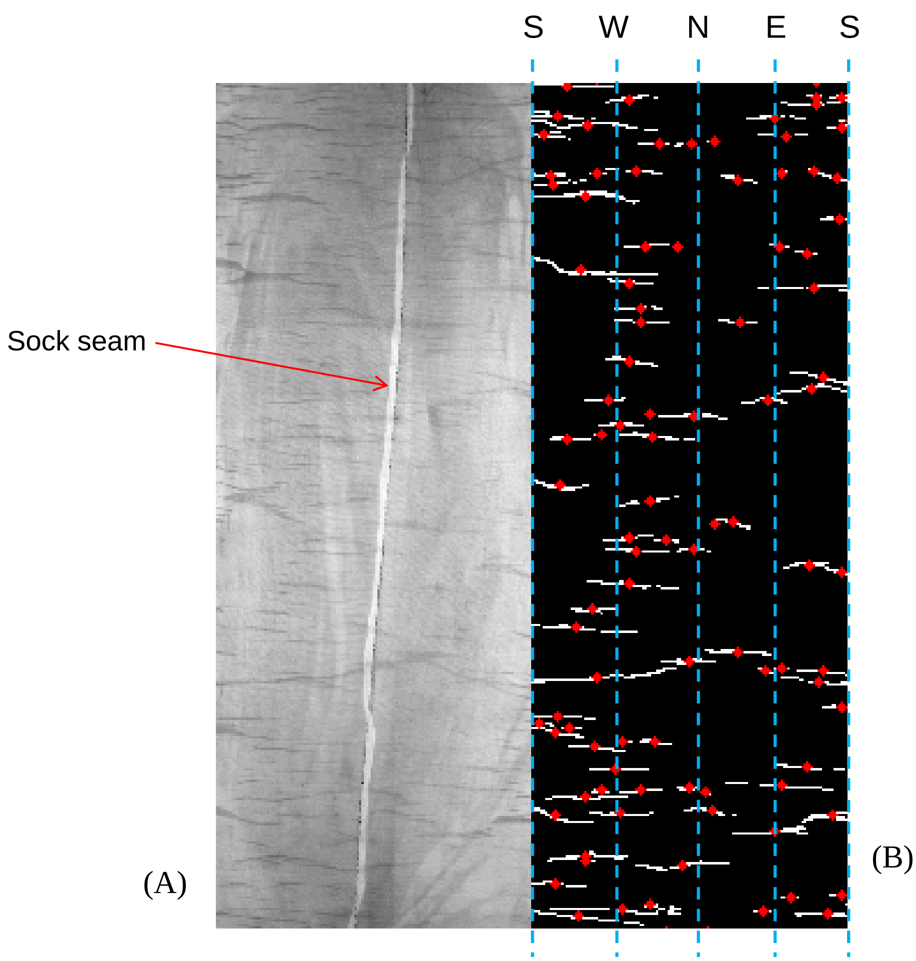


Figure 9. Test K: (A) black and white image of visual features from a portion of the FRPFM sock. (B) Centroids of individual features referenced to the FRPFM accelerometer directional orientation.

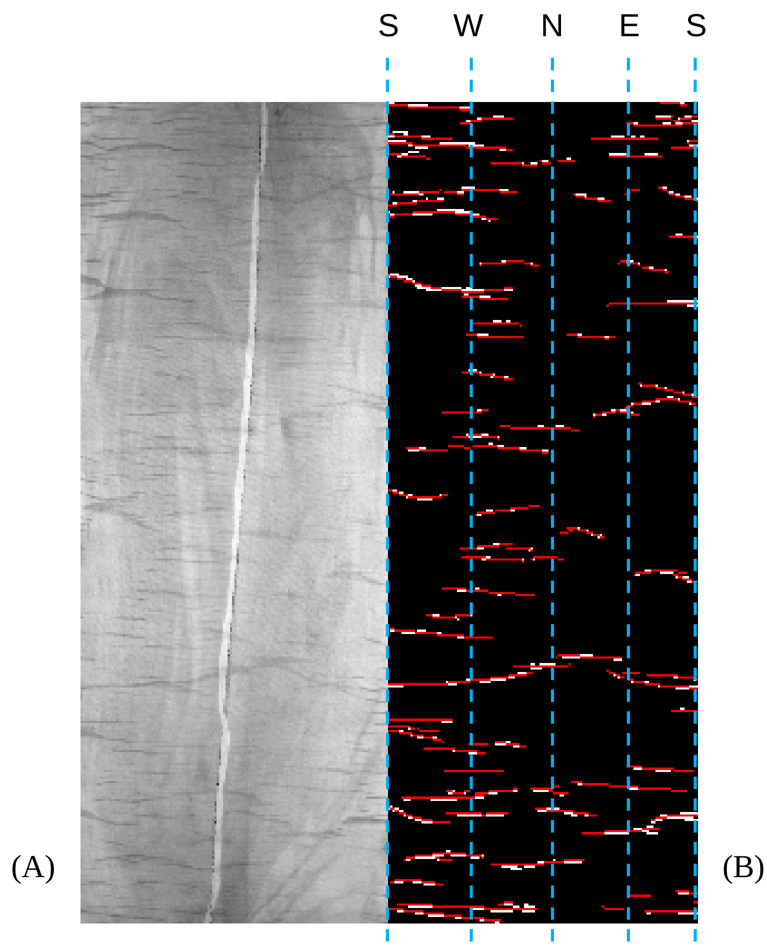


Figure 10. Test K: (A) Black and white image of visual features from a portion of the FRPFM sock. (B) Visual features with fitted sine function traces, which are used to estimate fracture depth, azimuth and dip.

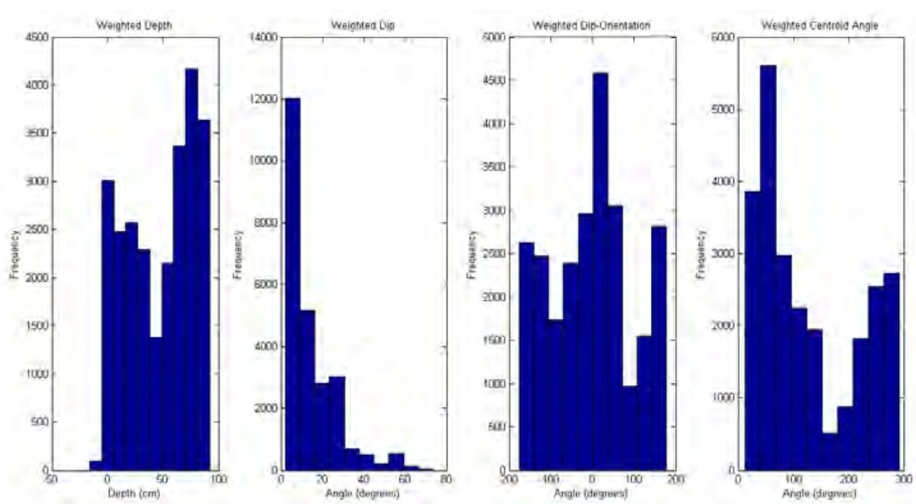


Figure 11. Test K: Histograms of fracture depth, dip, orientation (azimuth) and centroid angles.

Note: depth is the local depth along the 100-cm FRPFM interrogation zone.

Test M was performed to completion at NAWC but the results were compromised by vandalism and theft of equipment maintained at land surface during deployment. The FRPFM packers were damaged as a result, but the FRPFM prototype was recovered and repaired. There are no results available for report.

The final phase of field testing was performed during 2013 at the NAWC site. A total of five FRPFM deployments were performed (Tests N-R) along with 16 modified BHD tests. Tests N-Q were performed sequentially within zone D of 68BR (Figure 15), which is known to be a zone with higher flow and contaminant concentrations based upon previous studies by USGS (Shapiro, 2008; Tiedeman et al, 2010; and Lacombe, 2011). The initial depth of 95.12 ft-bgs within this zone was selected as a priority target based upon HRTP/TVP data collected by the University of Guelph that confirmed quantifiable flow at this depth. Test R was performed within zone F of 68BR (Figure 15), which also was expected to be a zone with quantifiable flow and contaminant concentrations based upon previous studies (Shapiro, 2008; Tiedeman et al., 2010; and Lacombe, 2011). HRTP/TVP measurements indicated flow at a target depth of 133 ft-bgs within zone F.

Because NAWC is an active pump and treat site, the flow conditions can be altered through use of the pump and treat extraction wells. Previously published work by the USGS demonstrated the benefit of such tests (Tiedeman et al., 2010). Results of the Tiedeman et al., 2010 study indicated a direct hydraulic connection between zones D and F in monitoring well 68BR (Figure 15) and extraction well 15BR. Well locations are provided in Figure 13.

Tests N and O were performed at the same deployment depth (95.12 ft-bgs) but with different pumping conditions at extraction well 15BR. The objective was to evaluate how the FRPFM performed under varied flow conditions. Test N was performed with a deployment duration of 8 days and a reduced extraction rate of 6.4 gallons per minute at 15BR. This was the minimum rate at which 15BR could be operated while still maintaining permitted contaminant extraction levels at the pump and treat boundary. BHD tests under these conditions indicated a specific discharge of 3.2 cm/day over the interrogation zone, with TCE and DCE mass flux values of 40,545 $\mu g/m^2$/day and 24,486 $\mu g/m^2$/day, respectively (Table 5). When the FRPFM was retrieved there were minimal to no visual indications of flow. FRPFM alcohol tracers indicated a specific discharge of 3.2 cm/day over the interrogation zone (Table 6). Analysis of the FRPFM sorbent indicated TCE and DCE mass flux values of 50,091 $\mu g/m^2$/day and 27,558 $\mu g/m^2$/day, respectively (Table 6).

Test O was performed with a deployment duration of 6 days and increased extraction rate of 13.7 GPM at 15BR. This is the typical extraction rate maintained at 15BR during regular operation of the pump and treat system. BHD tests under these conditions indicated only a slight increase in specific discharge to 3.4 cm/day over the interrogation zone when compared to Test N. TCE and DCE mass flux values also showed slight increases to 42,712 $\mu g/m^2$/day and 25,795 $\mu g/m^2$/day, respectively (Table 5). In stark contrast to Test N, however, when the FRPFM was retrieved there were visual indications of 68 discrete flowing features (Figures 12 and 13). Evaluation of the visual features indicated a specific discharge of 5.5 cm/day over the interrogation zone (Table 6). FRPFM alcohol tracers indicated a specific discharge of 3.8 cm/day over the interrogation zone (Table 6). Analysis of the FRPFM sorbent indicated TCE and DCE mass flux values of 148,849 $\mu g/m^2$/day and 55,647 $\mu g/m^2$/day, respectively (Table 6).

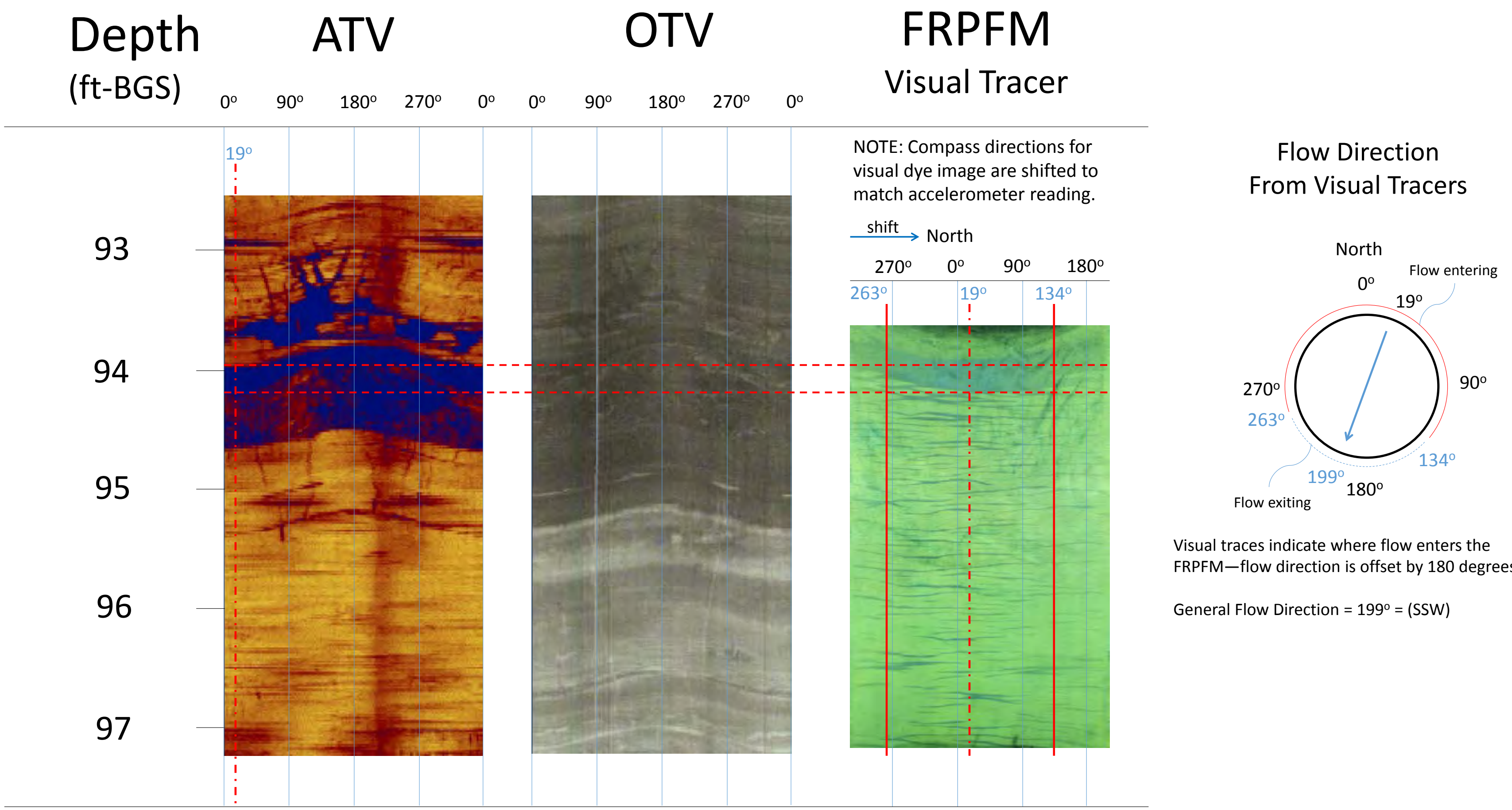


Figure 12. Test O comparison of ATV, OTV, and FRPFM visual tracer with inferred flow direction.

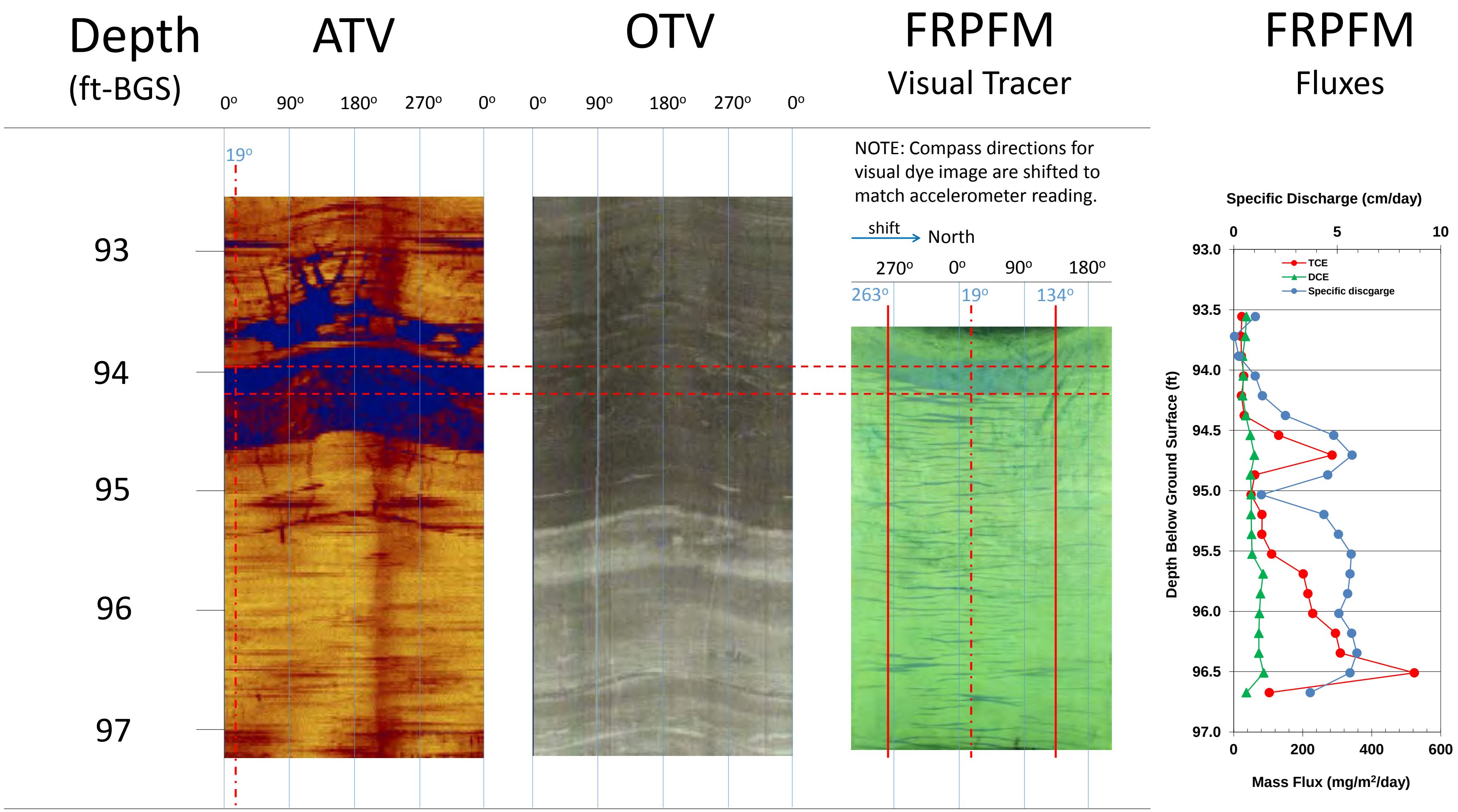


Figure 13. Test O comparison of ATV, OTV, FRPFM visual tracer and FRPFM fluxes.

Test O provides a complete demonstration of the full FRPFM technology suite with the results summarized in Figures 12 and 13. The FRPFM visual tracer sock provides a high-resolution distribution of the location and orientation of actively flowing fractures within the interrogation zone, which are compared to ATV and OTV images in Figure 12. The centroids of the visual features were used with the FRPFM accelerometer orientation to estimate a general groundwater flow direction of 199° (south southwest) Figure 12. The vertical distribution of FRPFM water and contaminant fluxes are also compared to ATV, OTV, and FRPFM visual features in Figure 13. It can be seen that there are considerable variations in specific discharge and TCE flux within the interrogation zone, and the FRPFM data collected allows for evaluation of the relative contribution to flow and contaminant flux on a per feature basis. More in depth analysis and comparison of results is provided in Section 6.3.

Tests P and Q were performed with same extraction rate as Test O (13.7 gallons per minute at 15BR), with Test P overlapping the upper half of the interrogation zone of Test O and Test Q overlapping the lower half of the interrogation zone of Test O. The intent was to evaluate how results vary based upon placement of the FRPFM within a larger zone of interest.

Test P was performed with a deployment duration of 7 days at a deployment depth of 93.62 ft-bgs. BHD tests indicated a specific discharge of 3.8 cm/day over the interrogation zone, with TCE and DCE mass flux values of 147,524 μg/m^2/day and 48,679 μg/m^2/day, respectively (Table 5). When the FRPFM was retrieved there extremely faint variations in visual tracers, but no conclusive visual indications of flow. FRPFM alcohol tracers indicated a specific discharge of 3.3 cm/day over the interrogation zone (Table 6). Analysis of the FRPFM sorbent indicated TCE and DCE mass flux values of 144,475 μg/m^2/day and 52,865 μg/m^2/day, respectively (Table 6).

Test Q was performed with a deployment duration of 8 days at a depth of 96.62 ft-bgs. BHD tests indicated a specific discharge of 2.3 cm/day over the interrogation zone, with TCE and DCE mass flux values of 155,791 μg/m^2/day and 40,803 μg/m^2/day, respectively (Table 5). When the FRPFM was retrieved there were faint visual indications of two discrete features along the same horizontal arc on the FRPFM at approximately 96.15 ft-bgs. The inferred flow direction from the faint visual features was east southeast (113E) (Figure 14). FRPFM alcohol tracers indicated a specific discharge of 2.1 cm/day over the interrogation zone (Table 6). Analysis of the FRPFM sorbent indicated TCE and DCE mass flux values of 145,523 μg/m^2/day and 51,888 μg/m^2/day, respectively (Table 6).

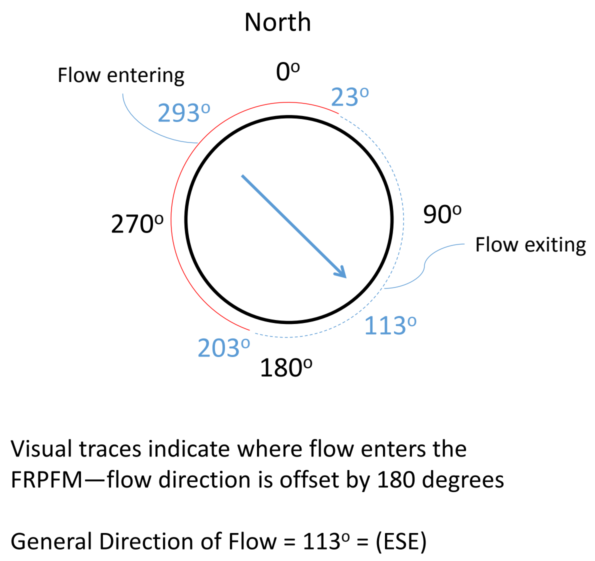


Figure 14. Test Q inferred general flow direction from faint visual features on FRPFM sock.

Test R was the final FRPFM deployment and was performed 68BR at a depth of 133.62 ft-bgs. The pump and treat extraction rates were maintained similar to Tests O, P and Q (13.7 gallons per minute at 15BR). BHD results indicated a specific discharge of 1.3 cm/day over the interrogation zone with TCE and DCE mass flux values of 28,473 µg/m^2/day and 6,680 µg/m^2/day, respectively (Table 5). Based upon the lower BHD specific discharge, a longer FRPFM deployment duration (15 days) was selected. When retrieved, there were faint but distinct visual indications of a circular feature (centroid at 134.75 ft-bgs) intersected by two high-angle fractures. Figure 15 provides a comparison of ATV/OTV images with FRPFM visual indications of the flowing circular feature and two high-angle fractures. The FRPFM images were processed using multiple filters to enhance the circular and high angle features. One negative side effect of image filtering was enhanced appearance of the weave pattern within the visual indication sock material, which could provide a false positive for flowing fractures when seen by an untrained observer. Evaluation of the visual features with the FRPFM accelerometer orientation provided a general groundwater flow direction of 288° (west northwest) Figures 15 and 16. FRPFM alcohol tracers indicated a specific discharge of 1.0 cm/day over the interrogation zone (Table 6). Analysis of the FRPFM sorbent indicated TCE and DCE mass flux values of 23,279 µg/m^2/day, and 33,072 µg/m^2/day respectively (Figure 17 and Table 6).

Discussion of analysis methods and comparison of results is provided in Section 6.

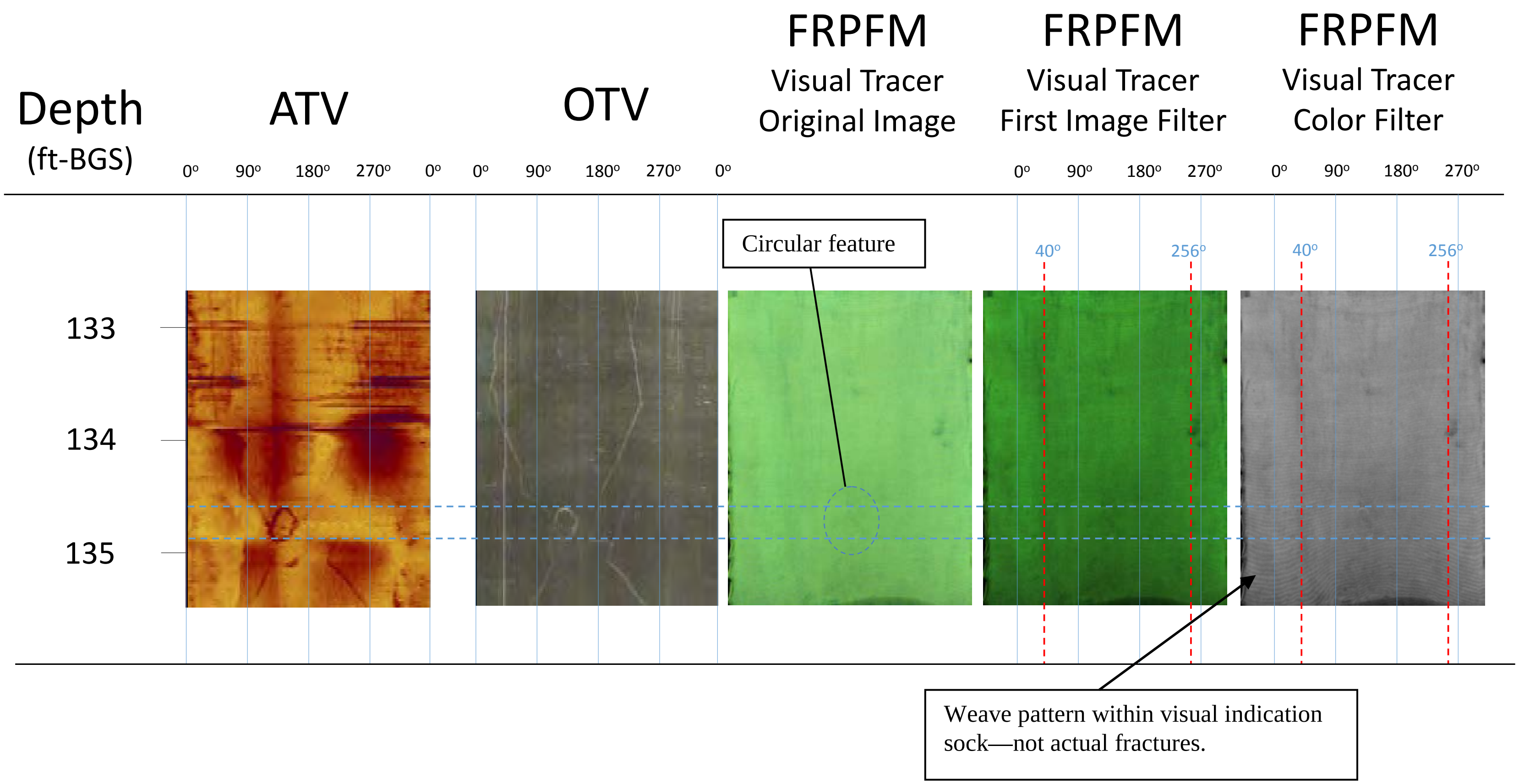


Figure 15. Test R Comparison of ATV/OTV with FRPFM visual indications of flowing circular feature intersecting two high-angle fractures.

The FRPFM images were processed using multiple filters to enhance the circular feature and high angle fractures.
Note: one side effect of image filtering was the enhanced appearance of weave pattern within the visual indication sock material.

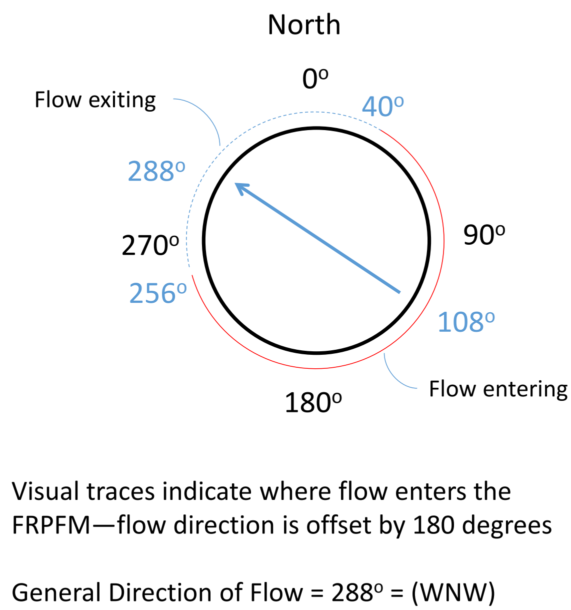


Figure 16. Test R inferred general flow direction from visual features on FRPFM sock (Figure 15).

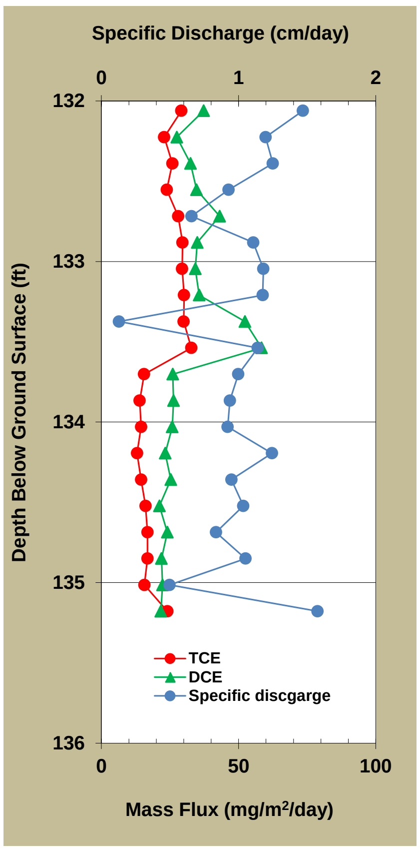


Figure 17. Test R vertical distribution of water and contaminant fluxes within FRPFM interrogation zone.

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6.0 PERFORMANCE ASSESSMENT

6.1 SUMMARY OF DATA TYPES AND PERFORMANCE OBJECTIVES

The FRPFM provides independent measures of six data types with regard to actively flowing fractures. Data types correspond to the quantitative performance objectives outlined in Table 1: 1) detection of flowing fractures, 2) fracture location (depth), 3) fracture orientation, 4) fracture flow direction, 5) groundwater flux (specific discharge), and 6) contaminant mass flux.

It is important to note that the FRPFM technology suite provides redundancy for data types 1, 2, and 5 as they are each simultaneously and independently measured by two different technology components of the FRPFM—the visual tracer and the alcohol tracers. Imagery of the visual indication sock provides high resolution measures for data types 1, 2, and 5. The alcohol tracers also provide measures of data types 1, 2, and 5 with the resolution of these measures defined by the size of the sampling interval of the FRPFM sorbent—smaller samples with higher frequency provide higher resolution.

Data type 3 and 4 are determined through evaluation of a visual tracer. Evaluation of the individual features provides information relative to fracture orientation (e.g. azimuth and dip), while referencing centroids for all individual features to magnetic north (based upon FRPFM accelerometer directional orientation) provides flow direction information.

Data types 5 and 6 are obtained independently from the elution of internal alcohol tracers from and the sorption of contaminant mass to the FRPFM sorbent. It should be noted that the ratio of FRPFM measures of contaminant mass flux and groundwater flux can be used to estimate flux average contaminant concentrations, which can be compared to current and previous measures of aqueous contaminant concentrations obtained from standard groundwater sampling and comparative technologies.

When including the functional redundancy for data types 1, 2, 5, and 6 as discussed above, the FRPFM effectively provides independent measures of 10 data types as outlined in Table 7. The data type IDs listed in Table 7 were established to indicate the quantitative performance objective to which each data type corresponds. These 10 data types are the basis for discussion of results, as each data type is evaluated through comparisons of FRPFM results to measures from at least one other competing technology. These comparisons are then used to evaluate FRPFM performance.

Table 7. Summary of data type comparisons for all technologies used to evaluate FRPFM performance.

Each data type is referenced to the appropriate performance objective (Table 1).

Data Type ID	Comparative Technologies		Performance Objective	
	Tech 1	Tech 2		
1A	HRTP	FRPFM visual tracer	1	Detection of flowing fracture
1B	HRTP	FRPFM alcohol tracers	1	Detection of flowing fracture
2A	ATV/OTV	FRPFM visual tracer	2	Fracture location (depth)
2B	ATV/OTV	FRPFM alcohol tracers	2	Fracture location (depth)
3	ATV/OTV	FRPFM visual tracer	3	Fracture orientation
4	TVP	FRPFM visual tracer	4	Fracture flow direction
5A	BHD	FRPFM visual tracer	5	Water flux
5B	BHD	FRPFM alcohol tracers	5	Water flux
6A	BHD	FRPFM sorbent	6	Contaminant flux
6B	BHD	FRPFM sorbent	6	Contaminant flux average concentration

6.2 FIELD DEMONSTRATION RESULTS

In the project Final Report, statistical analysis methods are presented in Section 6.2 that are then used in Section 6.3 to evaluate quantitative results for all FRPFM field tests. The discussion of results is organized based upon the performance objectives (Table 1) and corresponding quantitative data types (Table 7) used to evaluate each objective. The analyses and results are discussed in detail in Section 6.3 of the project Final Report.

A summary of the results for the quantitative performance objectives, based upon average percent difference between FRPFM and competing technologies, is provided in Table 8, which shows good agreement between FRPFM measures and those provided by alternative technologies. The results demonstrate that the FRPFM provides accurate, independent, and simultaneous measure of six data types: 1) detection of flowing fractures, 2) fracture location (depth), 3) fracture orientation, 4) fracture flow direction, 5) groundwater flux (specific discharge), and 6) contaminant mass flux. There is no other current technology that can currently measure all of these simultaneously.

Table 8. Summary of quantitative performance objectives with comparative results.

Performance Objective		Data Requirements	Success Criteria	Technology Comparison
Quantitative Performance Objectives				**Average Percent Difference**
1	Detection of flowing fractures	Measures from visible and non-visible FRPFM tracers and comparative technologies	Detect presence of flowing fractures +/- 10%	-0.42%
2	Fracture location (depth)	Measures from visible and non-visible FRPFM tracers and comparative technologies	Detect fracture location within +/- 10%	-0.04%
3	Fracture orientation	Visible dye measures and measures from comparative technology	Measurement validation to within *+/- 15%*	3.3 %
4	Fracture flow direction	Visible dye measures and measures from competing technology	Measurement validation to within *+/- 25%*	19.1%
5	Accuracy of water flux measurements	Measures from FRPFM and comparative technologies	Measurement validation to within *+/- 25%*	6.7%
6	Accuracy of contaminant flux measurements	Measures from FRPFM and comparative technologies	Measurement validation to within *+/- 25%*	2.0%

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7.0 COST ASSESSMENT

7.1 COST MODEL

The FRPFM is the only technology that provides simultaneous measurement of six data types (Table 8) within fractured rock wells: 1) detection of flowing fractures, 2) fracture location (depth), 3) fracture orientation, 4) fracture flow direction, 5) groundwater flux (specific discharge), and 6) contaminant mass flux. The FRPFM provides high resolution measurements over a specific interrogation zone (currently 1 meter). Due to the high resolution nature of the technology, FRPFM application is meant to be focused on high priority target zones and not intended as tool for screening flow conditions across an entire borehole. In order to select the priority target zones, baseline characterization should include at a minimum standard ATV and OTV logs, and aqueous contaminant concentrations from zones of interest. Ideally, it is beneficial to have preliminary indications of potential flow zones based upon comparative and complementary technologies, such as BHD and HRTP/TVP to help identify the priority zones for high resolution FRPM measurements.

The FRPFM technology currently functions through deployment of custom-built prototypes designed with a specified interrogation zone (typically 1 meter). Currently, prototypes exist for application in 4-inch and 6-inch fractured rock wells. Determining the price for application is based upon the number of wells to be evaluated, the number of target deployment zones within each well, and the resolution of FRPFM sorbent analysis for water and contaminant flux distributions. The cost of mobilization and demobilization are dependent upon site location. In order to estimate the cost of FRPFM deployment it is assumed that the technology will be used to investigate one well with one (1-meter) interrogation interval and a sampling resolution of 20 samples (5 cm depth resolution) for flux estimates.

7.2 COST DRIVERS

7.2.1 Cost Element: Mobilization

Mobilization encompasses required personnel and associated labor, planning, contracting, transportation/shipping requirements, permitting to secure regulatory approval for alcohol tracer use, and site preparation. The scale of mobilization will depend on the number of wells to be characterized.

7.2.2 Cost Element: Baseline Characterization

Baseline characterization encompasses required personnel and associated labor, investigation into available site-specific literature, a preliminary site visit, water level measurements, contaminant sampling and analysis, sample shipping, analytical laboratory costs, and residual waste handling. The scale of baseline characterization will depend on the number of wells to be characterized.

7.2.3 Cost Element: FRPFM

Deploying, extracting, and sampling the FRPFM will encompass required personnel and associated labor, capital equipment purchases, operator labor, operator training, raw materials, consumables, supplies, sampling, sample shipping, sample analysis, analytical laboratory costs, and residual waste handling. The scale of the FRPFM cost component will depend on the number interrogation zones to be investigated and the resolution of FRPFM sorbent analysis for water and contaminant flux distributions.

7.2.4 Cost Element: Alternative Technologies

The alternative technologies element encompasses costs of using alternative technologies including: BHD and HRTP/TVP in a FLUTe liner. With the exception of BHD, there are existing commercial entities that provide characterization services using the above technologies. For estimating costs of conducing borehole dilution, the following cost parameters will be tracked: transportation of personnel; materials and labor to construct a borehole dilution setup; shipping of equipment; water sampling; water sample analysis; analytical laboratory costs; and residual waste handling and all related labor related costs. The scale of the alternative technologies component will depend on the number of wells to be characterized.

7.2.5 Cost Element: Demobilization

Demobilization encompasses required personnel and associated labor, planning, contracting, transportation/shipping requirements. The scale of demobilization will depend on the number of wells to be characterized.

7.3 COST ANALYSIS

Because the FRPFM is the only device capable of providing high resolution simultaneous measurement of the six data types outlined in Table 8, there are no alternative methods available for direct comparison of cost. BHD provides an alternative method for measuring two of the six data types: water and contaminant flux. However, for low flow conditions (<10 cm/day), BHD test durations can approach 1 week requiring continuous staffing and maintenance (Test R at NAWC required a BHD test of 7 days to obtain stable contaminant flux estimate). HRTP and TVP provides an alternative method for measuring three of the six data types: presence of flowing fractures, fracture location, and flow direction. These methods have the added benefit that they provide characterization of these three measures over the entire depth of lined borehole. The TVP analysis used as basis of comparison in section 6 (Pehme et al., 2014) was performed in a lined borehole, which requires purchase of a FLUTe liner, if one is not already in use. As many sites actively use liners, the purchase of a FLUTe liner is considered an optional cost.

In order to provide an accurate estimate for FRPFM cost, the following conditions are assumed: all wells for testing are pre-existing (no drilling costs); minimal baseline characterization includes ATV/OTV; and aqueous contaminant concentrations obtained within target zones. Table 9 outlines the total cost for FRPFM deployment assuming the technology will be used to investigate one well with one (1-meter) interrogation interval and a sampling resolution of 20 samples (5 cm depth resolution) for flux estimates. For most FRPFM operations, mobilization

and demobilization are symmetric operations with similar costs, and the total mobilization and demobilization costs are combined to include all planning, travel, and salary. The FRPFM cost is broken out to show consumable materials and preparation, sample analysis, and interpretation of results. The total cost for FRPFM deployment, retrieval, sampling and analysis per the conditions outlined in Table 9 is $11,283. Table 10 provides a detailed breakdown of the cost to construct one FRPFM device. Once constructed, the FRPFM device can be used repetitively for approximately 25 deployments before routine maintenance is recommended and possible replacement of packer gum rubber may be required.

Table 9. FRPFM deployment cost.

1	Number of wells
1	Number of target intervals per well
1	Total number of interrogation intervals
20	Samples per FRPFM
20	Total number of samples
Costs	
Mobilization and Demobilization	
Travel	
2	Number of round trips
2	Days and nights per trip
$350	Airline ticket per trip
$70	Rental car per day (minivan)
$140	Rental car total
$120	Hotel per night
$240	Hotel per trip
$100	Fuel per trip
$36	Per diem (per person per day)
$72	Per diem per trip
$902	*Travel total*
$300	Shipping of equipment, supplies and samples
$1120	Salary and benefits cost (2 trips with 2 x 8-hour work days at $35/hour)
$2322	***Total for mobilization and demobilization***
FRPFM	
$500	FRPFM AC-felt and visual dye sock preparation
$4000	Sample analysis ($300 per sample for 20 samples)
$700	Interpretation of results (20 hours at $35/hour)
$5200	***FRPFM Total***
$7522	Direct Cost
$3761	IDC
$11,283	**Total Cost**
Construction Cost of one FRPFM Device (for 6-inch borehole with 1-meter interrogation zone)	
$1989	Including materials and labor (detailed cost is provided in Table 24)

Note: Construction cost does not include consumables such as AC-felt and visual dye sock.

Table 10. FRPFM construction cost.

Cost to construct one FRPFM (6-inch diameter with 1-meter interrogation zone)[1]					
Item	**Unit Cost**		**Unit**		**Total Cost**
Gum rubber for packers (4" ID, 4.5" OD)[2]	$33.90	per foot	4.5	ft	$152.55
Gum rubber for core (3" ID, 3.5" OD)[2]	$20.00	per foot	3.5	ft	$70.00
PVC stock (rods) for packers (6"OD)	$96.00	per foot	4.5	ft	$432.00
Swageloc fittings	$12.00	each	8		$96.00
Tubing	$0.92	per foot	300	ft	$276.00
Low Profile Clamps	$7.60	each	10		$76.00
Stainless steel shield (material)	$40.60	per foot	10	ft	$406.00
Man hours (machinist)	$20.00	per hour	24	hours	$480.00
				Total	$1,988.55

[1] Construction cost does not include consumables such as AC-felt and visual dye sock.
[2] Once constructed, the FRPFM device can be used repetitively for approximately 25 deployments before routine maintenance is recommended and possible replacement of packer gum rubber may be required.

To provide an accurate BHD cost estimate for comparison to FRPFM, it was assumed that the technology would be used to investigate one well with one (1-meter) interrogation interval with a total of 20 aqueous samples over the duration of the BHD test. Mobilization and demobilization costs are very similar to FRPFM with the primary difference being the amount of time staff must be on site to monitor BHD testing. It was assumed that a BHD test duration of 5 days would provide a reliable estimate for contaminant flux. Depending on the flow conditions, shorter duration tests (24 hour) will cost less while still provide reliable water flux estimates, but contaminant flux estimates would not be viable. The total cost for BHD testing per the conditions outlined in Table 11 is $11,295.

Table 11. BHD cost.

1	Number of wells
1	Number of target intervals per well
1	Total number of interrogation intervals
20	Total number of samples
Costs	
Mobilization and Demobilization	
Travel	
1	Number of round trips
5	Days and nights per trip
$350	Airline ticket per trip
$70	Rental car per day (minivan)
$350	Rental car total
$100	Hotel per night
$500	Hotel per trip
$100	Fuel per trip
$36	Per diem (per person per day)
$180	Per diem per trip
$1480	*Travel total*
$300	Shipping of equipment, supplies and samples
$1400	Salary and benefits cost (1 trip with 5 x 8-hour work days at $35/hour)
$3180	***Total for mobilization and demobilization***

Table 11. BHD cost (continued).

FRPFM	
$500	FRPFM AC-felt and visual dye sock preparation
$4000	Sample analysis ($300 per sample for 20 samples)
$700	Interpretation of results (20 hours at $35/hour)
$5200	***FRPFM Total***
$7522	Direct Cost
$3761	IDC
$11,283	**Total Cost**
Construction Cost of one FRPFM Device (for 6-inch borehole with 1-meter interrogation zone)	
$1989	Including materials and labor (detailed cost is provided in Table 24)

To provide an HRTP/TVP cost estimate for comparison to FRPFM, it was assumed that the technology would be used to characterize flow over the entire depth of a 200-ft well. The cost of mobilization was considered to be comparable to FRPFM with the primary difference being that typical HRTP/TVP testing takes about 3 days per borehole. As mentioned previously, the purchase of a flute liner for HRTP/TVP testing is included as an optional cost. The total cost for HRTP/TVP testing, per the conditions outlined in Table 12, is $6,722 if a FLUTe liner is already available, and $11,722 if the optional cost of a FLUTe liner is included.

Table 12. HRTP/TVP cost.

1	200-ft well
Costs	
Mobilization and Demobilization	
Travel	
1	Number of round trips
2	Days and nights per trip
$350	Airline ticket per trip
$70	Rental car per day (minivan)
$140	Rental car total
$100	Hotel per night
$200	Hotel per trip
$100	Fuel per trip
$36	Per diem (per person per day)
$72	Per diem per trip
$862	*Travel total*
$300	Shipping of equipment, supplies and samples
$560	Salary and benefits cost (1 trip with 3 x 8-hour work days at $35/hour)
$1722	***Total for mobilization and demobilization***
HRTP/TVP	
$5000	HRTP/TVP without mobilization (typically 3 days work)
$6722	**Total Cost**
$5000	Optional cost of flute liner for 200-ft well with installation
$11,722	Total HRTP/TVP optional with liner
Rental costs for HRTP/TVP equipment	
$1667	per day

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8.0 IMPLEMENTATION ISSUES

8.1 ENVIRONMENTAL CHECKLIST

Depending on site conditions, permits may be required for permission to release small quantities of food-grade tracers into the aquifer. A standard list of tracers is available, and no issues have been experienced with previous permit requests.

8.2 OTHER REGULATORY ISSUES

Continuous contact with appropriate site managers is strongly recommended through the duration of all testing to avoid issues with any site-specific regulations.

8.3 END-USER ISSUES

The FRPFM technology currently functions through deployment of custom-built prototypes designed with a specified interrogation zone (typically 1 meter). Currently, prototypes exist for application in 4-inch and 6-inch fractured rock wells. Deployment, retrieval, and sampling is straightforward and has been demonstrated to field technicians from the University of Guelph and USGS who experienced minimal issues with methodology transfer.

As technology development continues, refinements will be made and applied to future prototypes (such as expanded interrogation zone). Site specific refinements can be made as needed.

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APPENDIX A

POINTS OF CONTACT

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